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THÈSE



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Assessing the Potential of the Physical Internet for City Logistics Activities in Developing Countries

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SUMMARY

This research work identifies the challenges developing countries face in city logistics, including traffic congestion and poor infrastructure. The Physical Internet (PI) is proposed as a potential solution. Based on a state of the art on PI research, the work elaborates research questions related to how can the principles of the PI be implemented in the context of city logistics in developing countries? The thesis develops a conceptual contribution regarding how to implement PI concepts in city logistics in developing countries. Then technical and experimental contributions are proposed, including a hybrid simulation model and a real industrial case study. Numerical results demonstrate significant performance improvements using PI concepts, with up to 75% savings in logistics costs, 61% in carbon footprint and 55% in quality of service. The study suggests finally that implementing PI concepts could greatly enhance the sustainability and economy of developing countries.

Keywords: Developing Countries, Physical Internet, City Logistics, Urban Logistics, Last-Mile Delivery, Simulation, Cambodia.

RESUME

Ce travail de recherche identifie les défis auxquels les pays en développement sont confrontés en matière de logistique urbaine. L'Internet physique (IP) est envisagé comme une solution potentielle. Sur la base d'un état de l'art, le travail élabore des questions de recherche liées à la manière dont les principes de l'IP peuvent être mis en œuvre dans le contexte de la logistique urbaine des pays en développement. La thèse développe une contribution conceptuelle visant à définir des scénarios concrets d'implémentation. Ensuite, des contributions techniques et expérimentales sont proposées, notamment un modèle de simulation hybride et une étude de cas industrielle réelle. Les résultats démontrent des améliorations significatives des performances, avec jusqu'à 75% d'économies sur les coûts, 61% sur l'empreinte carbone et 55% sur la qualité de service. L'étude conclut enfin que la mise en œuvre des concepts d'IP pourrait grandement améliorer la durabilité et l'économie de ces pays.

Mots clés : Internet Physique, Logistique urbaine, Simulation, Pays en développement, Logistique du dernier kilomètre, Cambodge

RESUME LONG EN FRANÇAIS

Chapitre 1

Caractéristiques Générales et Défis des Pays en Développement

L'étude de recherche vise à répondre aux défis de la logistique urbaine auxquels sont confrontés les pays en développement, notamment en Asie du Sud-Est. Cette section fournit une compréhension détaillée des caractéristiques critiques des pays en développement, telles que les défis en matière de revenus, d'affaires, de société et de développement du territoire, et la manière dont ces défis conduisent à des problèmes de logistique urbaine. Ces défis comprennent les embouteillages, les routes dangereuses, les infrastructures de mauvaise qualité, les véhicules coûteux et peu fiables, le taux de croissance élevé de la population, l'urbanisation, etc. En outre, les pays en développement sont confrontés à divers défis tels que la faiblesse des revenus, la dépendance à l'égard de secteurs spécifiques, la faible productivité, les possibilités d'emploi limitées, les carences en matière de santé et d'éducation, la corruption et les problèmes spécifiques de logistique urbaine.

Cette section examine les caractéristiques générales des pays en développement, y compris les différents systèmes de classification basés sur des facteurs tels que le revenu national et l'index de développement humain. Elle met également en évidence les caractéristiques communes des pays en développement, telles que le faible revenu, la forte croissance démographique, la dépendance à l'égard des secteurs primaires, l'insuffisance des infrastructures et l'urbanisation rapide.

L'étude se concentre sur la région de l'Asie du Sud-Est, qui se compose de onze pays aux caractéristiques diverses, dont la plupart sont considérés comme des pays en développement. Alors que des pays comme Singapour et Brunei sont déjà développés, d'autres se débattent avec un faible PIB par habitant et sont confrontés à des défis majeurs tels que le changement climatique, l'agriculture, l'éducation, la santé, l'énergie, les infrastructures et les transports. Les pays en développement, y compris ceux de l'Asie du Sud-Est, sont confrontés à des problèmes de développement des revenus liés à une croissance économique lente et à des coûts commerciaux élevés, à des problèmes de développement des entreprises liés à l'agriculture et au commerce, à des problèmes de développement social tels que la croissance démographique, les inégalités, les problèmes de santé et d'éducation, et à des problèmes d'aménagement du territoire dus à une urbanisation rapide et à des contraintes d'infrastructure.

Les Défis de la Logistique Urbaine pour les Pays en Développement

Cette section aborde le concept de logistique urbaine, qui implique la gestion des activités de transport de marchandises dans une ville afin d'améliorer les opérations logistiques et de soutenir le développement économique et social tout en réduisant les nuisances associées au transport urbain. Cette section se concentre sur la logistique urbaine dans les pays en développement et met en évidence les défis auxquels ils sont confrontés, tels que des capacités logistiques inadéquates, une infrastructure médiocre, une adoption limitée des avancées technologiques et des défis spécifiques liés à la croissance démographique, aux préoccupations

environnementales et à la congestion du trafic. La recherche dans ce domaine appliqué aux pays en développement et il est nécessaire d'aborder les questions liées à l'infrastructure, à l'équipement, à la politique et aux opérations pour améliorer l'efficacité et l'efficience de la logistique urbaine dans les pays en développement.

Le Cas de la Ville de Phnom Penh

L'urbanisation rapide et les problèmes de circulation à Phnom Penh, au Cambodge, se sont aggravés en raison de la faiblesse du système de transport public et de l'augmentation du nombre de véhicules. Les applications de covoiturage ont gagné en popularité, ce qui a eu un impact sur les déplacements des passagers et la livraison du dernier kilomètre. L'utilisation de modes de transport adaptés, tels que les motos, les auto-rickshaws et les tuk-tuks, reste populaire dans la ville. Le manque de places de stationnement entraîne le stationnement sur les trottoirs, ce qui réduit l'accessibilité des piétons et contribue à la congestion du trafic. L'intégration de systèmes de transport adaptés de petite taille aux transports en commun peut améliorer la connectivité, la commodité et la rentabilité des options de transport, tout en offrant des perspectives d'emploi aux opérateurs.

Énoncé du Problème

Les pays en développement ont donc du mal à gérer leurs activités logistiques urbaines de manière durable et à soutenir leur économie. Bien qu'il soit nécessaire d'investir dans de nouvelles infrastructures et de nouveaux moyens de transport, il faut parfois des décennies pour obtenir des résultats tangibles. Le chapitre 1 a également suggéré qu'une solution pourrait consister à utiliser les actifs et les ressources existants, mais différemment. Avec une telle ambition, l'Internet Physique (PI) a été identifié comme un candidat potentiellement pertinent pour améliorer les activités de logistique urbaine des pays en développement.

Malgré les efforts déployés pour améliorer la situation, le problème reste critique. Ce projet de recherche vise à améliorer les performances des activités logistiques urbaines des pays en développement en utilisant les actifs et les ressources existants, en se concentrant sur l'amélioration du transport de marchandises dans les zones urbaines. Le projet recherche des solutions innovantes, en tenant compte des caractéristiques et des besoins uniques des pays en développement, et explore le potentiel du PI en tant que levier d'amélioration.

Chapitre 2

Le chapitre 2 donne un aperçu des travaux de recherche sur le PI et de la manière dont ils peuvent être envisagés dans le contexte des pays en développement. Les questions de recherche sont formulées sur la base de ce matériel exhaustif, à savoir comment les principes du PI peuvent être mis en œuvre dans le contexte de la logistique urbaine dans les pays en développement, comment l'application des concepts du PI peut être évaluée en termes d'impact sur la performance, et quels sont les avantages que l'on peut attendre de la mise en œuvre du PI dans le cas de la logistique urbaine dans les pays en développement. Pour répondre à ces questions, la recherche propose une méthodologie de recherche en sciences de la conception comprenant quatre phases principales et neuf étapes.

Hypothèse de Recherche : Le PI Comme Solution Potentielle

Le PI est un concept qui intègre et optimise les réseaux de transport physique pour créer un système logistique mondial plus efficace et plus durable. Il vise à améliorer l'efficacité, la durabilité et la résilience en s'appuyant sur des réseaux interconnectés, des protocoles de collaboration normalisés, des conteneurs modulaires et des interfaces intelligentes. Le PI encourage le transport intermodal, l'utilisation des technologies numériques, les modes de transport alternatifs et les sources d'énergie durables. Bien que sa mise en œuvre pose des problèmes, le PI a le potentiel de révolutionner le secteur des transports et de la logistique, en particulier dans les pays en développement, en améliorant la connectivité, l'efficacité et la durabilité. Ce projet de recherche vise à déterminer si le PI peut améliorer les performances des activités de transport de marchandises dans les villes des pays en développement en utilisant les moyens et les infrastructures existants.

Plusieurs études ont été publiées sur le PI, portant sur les concepts, les évaluations, la collaboration, les composants et les installations innovantes. Les concepts du PI impliquent un réseau à quatre niveaux soutenant un modèle commercial innovant, tandis que la collaboration est cruciale pour la mise en œuvre du PI. Les évaluations du PI mettent en évidence ses avantages potentiels en termes de performances environnementales, économiques et sociales. Les composants du PI comprennent les PI conteneurs, les PI transporteurs (camions et véhicules) et les PI nœuds (PI nodes/PI hubs). Des installations innovantes telles que l'analyse des big data, la blockchain et les systèmes intelligents sont utilisées pour soutenir la mise en œuvre du PI.

Formulation des Questions de Recherche

Ce projet de recherche vise à résoudre les problèmes de transport dans les pays en développement en se concentrant sur la logistique urbaine et en proposant des solutions nouvelles et innovantes. Il se concentre sur la mise en œuvre des principes du PI dans la logistique urbaine afin d'améliorer l'efficacité du transport, de réduire les délais, d'améliorer la ponctualité des livraisons, de minimiser les déchets, d'optimiser les coûts et de réduire l'empreinte carbone. Le projet de recherche vise à répondre à trois questions principales :

- 1) Comment les principes du PI peuvent-ils être mis en œuvre dans le contexte de la logistique urbaine dans les pays en développement ?
- 2) Quel est l'impact de l'application des concepts du PI sur les performances de la logistique urbaine dans les pays en développement ?
- 3) Quels sont les avantages concrets de la mise en œuvre du PI dans la logistique urbaine des pays en développement ?

L'étude comprend la conception de scénarios applicables, la création d'un banc expérimental pour l'évaluation et la réalisation d'une étude de cas d'application sur le terrain.

Méthodologie de Recherche

La méthodologie de recherche employée dans cette étude est une approche de recherche en science de la conception, adaptée des cadres et méthodologies existants. Elle comprend une étude de terrain pour comprendre le contexte et les défis du transport dans les pays en

développement, une analyse quantitative des performances actuelles, une étude bibliographique pour identifier les lacunes et les outils dans la littérature, la formulation de problèmes et d'hypothèses scientifiques, la modélisation détaillée et la justification des méthodes de modélisation, l'expérimentation et l'évaluation. La méthodologie suit un processus en neuf étapes, comprenant la sélection d'un cas représentatif, la construction de modèles numériques, la modélisation de l'environnement, la simulation des comportements, la mesure des performances, la conception de scénarios alternatifs, la simulation de ces scénarios, la mesure de leurs performances et la formulation de recommandations.

Chapitre 3

Le chapitre 3 a développé une contribution conceptuelle en évaluant l'accessibilité et les niveaux d'intérêt de chaque concept de PI et a conclu que les priorités pour résoudre l'énoncé du problème devraient être le partage de l'information et les systèmes normalisés, les activités collaboratives à multiples facettes et les interconnexions entre les parties prenantes du système ouvert. Un ensemble de scénarios a été conçu pour mettre le PI en pratique afin d'améliorer la livraison des marchandises dans le contexte de la logistique urbaine dans les pays en développement. Ces scénarios ont été organisés par la mise en œuvre de PI-hubs, de systèmes de transport à la demande et de services, et par le partage des actifs.

Concepts Fondamentaux de la Logistique Urbaine Orientée PI

La logistique urbaine orientée PI vise à améliorer la logistique urbaine en réduisant la congestion, les émissions et les impacts négatifs tout en améliorant les services de livraison grâce au suivi en temps réel, à l'optimisation des itinéraires et aux modes de transport alternatifs. Elle fait appel à des concepts tels que les réseaux intermodaux mondiaux, le partage d'informations, les activités collaboratives, l'architecture distribuée, l'interconnexion des parties prenantes, les conteneurs modulaires, la mobilité intégrée des personnes et la logistique du fret, l'intégration de la planification urbaine, la durabilité, la visibilité, l'efficacité et l'innovation. Ces concepts favorisent des opérations logistiques efficaces et durables, la coordination entre les parties prenantes et l'intégration de la logistique dans les systèmes urbains.

D'après l'étude de (Crainic et Montreuil, 2016), l'évaluation de la logistique urbaine orientée vers le PI pour les pays en développement révèle que si certains concepts, tels que le partage de l'information et les systèmes normalisés, les activités collaboratives et l'interconnexion des parties prenantes, ont un potentiel d'amélioration, d'autres, tels que le réseau intermodal mondial et l'intégration de la planification urbaine, posent des défis considérables. Les pays en développement manquent souvent de capacités d'interconnexion et peinent à se spécialiser dans la logistique, ce qui se traduit par une baisse de la qualité et de l'efficacité. Cependant, l'architecture distribuée et l'intégration de la mobilité des personnes et de la logistique du fret sont déjà répandues dans ces pays. L'utilisation de conteneurs logistiques modulaires est rare, mais plus faisable en raison de la croissance soutenue. La durabilité, la visibilité, l'efficacité et l'innovation se heurtent à des obstacles dus aux limitations technologiques et à l'accent mis sur les performances de base. Les domaines d'amélioration prioritaires sont le partage de l'information, la collaboration et l'interconnexion des parties prenantes. Les solutions proposées

tireront parti des moyens et infrastructures existants pour améliorer les performances du transport de marchandises.

Modèle de Base

Le modèle de base pour l'évaluation des avantages des solutions orientées PI est établi en utilisant comme référence une entreprise cambodgienne de commerce en ligne appelée "Little Fashion Company" dans la ville de Phnom Penh. Le modèle repose sur l'hypothèse d'un centre de distribution unique doté d'une capacité de stockage infinie et de délais de préparation des commandes constants. L'entreprise dispose de sa propre flotte de véhicules pour les livraisons, et le processus d'exécution des commandes comprend le tri des commandes par emplacement, la préparation et l'emballage, la confirmation de l'heure de livraison avec les clients et la livraison des colis. En outre, nous avons fait l'hypothèse que tous les colis sont livrés au client dans ce scénario.

Les modèles orientés PI proposés se composent de trois éléments principaux : les PI-conteneurs, les PI-nœuds et les PI-movers. Les PI-conteneurs sont des conteneurs normalisés gérés par diverses entreprises, les PI-nœuds sont des lieux de réception, de stockage et de transfert des conteneurs, et les PI-movers sont des véhicules utilisés pour déplacer et manipuler les conteneurs.

Modèles Orientés PI : Modèle PI-Hub

Dans le scénario n° 1, l'introduction de PI-hubs en tant que plates-formes de transbordement permet un transfert efficace des colis entre les modes de transport et facilite la livraison du dernier kilomètre. Dans ce scénario, les PI-hubs reçoivent les marchandises entrantes et les transfèrent directement aux véhicules sortants sans stockage d'inventaire. Le processus d'exécution des commandes comprend le tri, la préparation, l'emballage, la consolidation et la livraison, tous les paquets transitant par un PI-hub avant d'atteindre les clients.

Modèles Orientés PI : Modèle PI-Mover à la Demande

Dans le scénario n° 2, il est proposé de créer un réseau de transport partagé et interopérable en utilisant les moyens de transport existants dans les pays en développement, tels que les tuk-tuks et les taxis-motos, pour transporter des marchandises à la demande. Le processus consiste à trier les marchandises dans des PI-hubs, à organiser des ramassages avec des fournisseurs de véhicules à la demande et à livrer les marchandises à l'endroit où se trouve le client. Le partage d'informations en temps réel et la collaboration entre les parties prenantes sont essentiels dans ce scénario.

Modèles Orientés PI : Modèle PI-Réseau

Le scénario n° 3 vise à explorer le partage des ressources entre deux entreprises distinctes opérant dans la même zone géographique, en se concentrant sur la livraison du dernier kilomètre. Les entreprises partagent des installations et des processus, utilisent des PI-hubs communs et suivent les modalités de transport proposées dans le scénario n° 2. La mise en commun des tournées de livraison du dernier kilomètre entre les deux entreprises permet d'améliorer l'efficacité du transport et d'obtenir des effets positifs. Le scénario implique l'utilisation d'un réseau PI, où les transporteurs collaborent et optimisent les itinéraires par le biais de plateformes PI ouvertes (open PI-hubs), ce qui permet de disposer d'informations

locales et en temps réel pour mettre à jour l'itinéraire optimal de chaque envoi. Les systèmes décentralisés, les protocoles de transport et les protocoles de collaboration sont essentiels pour gérer ce réseau de transport interconnecté et décentralisé, ce qui permet de réduire les niveaux de stocks et d'améliorer l'efficacité de la logistique urbaine.

Chapitre 4

Le chapitre 4 a développé les contributions techniques et expérimentales du travail de recherche en établissant un modèle de simulation hybride spécifique basé sur la modélisation à base d'agents et la simulation à événements discrets. Il comprend la définition d'indicateurs de performance spécifiques capables de mesurer les impacts potentiels des scénarios conçus au chapitre 3 par rapport au scénario de base. La contribution expérimentale est développée sur la base d'un cas industriel réel lié aux activités logistiques du commerce électronique dans la ville de Phnom Penh (Cambodge). Les résultats numériques montrent les avantages évidents de l'utilisation des PI-hubs et en particulier des systèmes de transport à la demande et "as-a-service", qui permettent des économies très substantielles allant jusqu'à 55 % pour les délais, 61 % pour l'empreinte carbone et 75 % pour les coûts logistiques. Toutefois, l'étude présente certaines limites, qui sont également discutées.

Globalement, l'étude conclut que l'utilisation de certains concepts de PI pourrait améliorer considérablement les performances des activités de logistique urbaine dans les pays en développement sans investissement particulièrement important. L'étude propose plusieurs perspectives de recherche, notamment l'utilisation du PI dans différents contextes et le développement d'outils d'aide à la décision pour la mise en œuvre du PI dans la logistique urbaine.

Contexte de la Modélisation de Simulation

La modélisation de simulation est une technique utilisée pour optimiser les systèmes en créant des modèles qui représentent des problèmes réels dans un environnement sans risque. Il existe trois principaux types de méthodes de modélisation de simulation : la simulation à événements discrets (DES), la dynamique des systèmes (SD) et la modélisation à base d'agents (ABM), chacune ayant son propre niveau d'abstraction et convenant à différents types de systèmes. Ces méthodes peuvent être utilisées individuellement ou combinées dans des approches multi-méthodes pour traiter des problèmes complexes du monde réel et fournir une meilleure compréhension du comportement du système dans le temps.

Le Modèle Proposé

Le modèle proposé est une technique de simulation hybride qui combine la modélisation à base d'agents (ABM) et la simulation à événements discrets (DES) pour évaluer les indicateurs de performance de la logistique urbaine dans les pays en développement. Il implique la création d'un modèle de simulation multi-méthodes qui capture la nature complexe et dynamique du système, en considérant des facteurs tels que les parties prenantes en tant qu'agents autonomes, les systèmes d'information géographique (GIS) pour l'environnement de l'agent, et le processus de livraison du dernier kilomètre. L'ABM est utilisé pour modéliser les comportements et les interactions des parties prenantes, tandis que le DES est utilisé pour représenter la séquence des

opérations et les durées incertaines. Le modèle intègre des attributs et des méthodes pour décrire les caractéristiques et les comportements des agents, spécifie les interactions et les relations entre les agents et utilise un environnement GIS pour représenter fidèlement le contexte géographique. Dans l'ensemble, le modèle proposé vise à capturer le comportement émergent du système dans la logistique urbaine des pays en développement.

Les Agents Dans le Modèle

Les modèles proposés décrivent différents types d'agents dans un modèle de simulation pour un système de livraison au dernier kilomètre. Les agents clients sont chargés de générer des commandes sur la base de fichiers de données et de simuler le comportement des clients. Ils disposent d'attributs tels que l'identifiant et la localisation du client (ID), et de méthodes telles que la définition du centre le plus proche et l'ajout de nouveaux clients à la simulation.

Les agents du centre principal (main hub) gèrent le traitement des livraisons et la logistique sur la base de règles établies. Ils ont des attributs tels que l'emplacement et des méthodes pour filtrer les véhicules disponibles et trouver l'agent le plus proche par itinéraire.

Les agents des centres locaux (local hub) servent de centres de transbordement et d'échange de transport. Ils ont des attributs tels que l'emplacement et des méthodes pour filtrer les motos et les véhicules de flotte et trouver l'agent le plus proche par itinéraire.

Les agents véhicules, y compris les camions, les tuk-tuks et les motos, sont responsables de la livraison des produits. Ils possèdent des attributs tels que l'identification (ID), la vitesse, la capacité et des méthodes de déplacement, de calcul de la distance et de recherche de l'agent le plus proche par l'itinéraire.

Ces agents collaborent et interagissent les uns avec les autres dans le cadre du processus de simulation, facilité par l'agent de commande qui gère la communication et le flux d'informations. Le processus implique que les clients passent des commandes, que les principaux centres reçoivent les commandes et que des lots de commandes soient créés pour une gestion efficace. Les commandes sont ensuite traitées en fonction de différents scénarios, impliquant des centres locaux et la livraison finale aux clients.

Le modèle de simulation utilise divers paramètres pour simuler le comportement des agents et évaluer le processus d'exécution. Les commandes des clients sont lues à partir d'un fichier externe et l'agent de commande stocke les détails de la commande. Le modèle optimise le transport en regroupant les commandes par lots et en les redirigeant vers des plates-formes locales avant la livraison finale.

Globalement, le modèle représente l'interaction et le flux d'informations entre différents agents afin de simuler et d'optimiser le processus de livraison du dernier kilomètre.

L'Environnement des Agents

La section traite de l'environnement des agents de simulation dans le modèle et du défi que représente la mise en œuvre de modèles de trafic réalistes. Les auteurs ont trouvé trois sources de données, dont une enquête menée par l'équipe d'experts en transport, des rapports de la JICA et de la municipalité de Phnom Penh, et des données provenant d'un cas industriel réel à Phnom Penh, pour recueillir des informations sur les schémas de circulation dans la ville. Sur la base de ces données, ils ont observé que les embouteillages sont un problème persistant tout au long de

la journée, que chaque zone a un schéma de circulation unique et que les motos ont tendance à être plus rapides que les tuk-tuks et les voitures. Pour modéliser les embouteillages, les auteurs ont développé un module central de trafic qui définit dynamiquement les vitesses moyennes de déplacement en fonction de divers facteurs. Ils fournissent un schéma de circulation détaillé pour différents types de véhicules et différentes heures de la journée à Phnom Penh.

Bien entendu, l'étude doit s'appuyer sur des hypothèses commerciales. L'entreprise fonctionne selon le principe du premier entré, premier sorti (FIFO), avec une capacité de stockage illimitée et des temps de préparation des commandes constants. Le modèle tient compte de la disponibilité des véhicules de transport, de leur vitesse en fonction de l'encombrement du trafic et de l'acheminement des véhicules à l'aide de l'algorithme du chemin le plus court. Les clients ont la possibilité de retirer les colis pour économiser sur les coûts de livraison, et tous les clients sont supposés être présents à leurs emplacements spécifiés. Cependant, certains facteurs tels que les préférences des clients pour une livraison plus rapide, les retards de maintenance des véhicules, les conditions de circulation, les fenêtres de livraison préférées, les zones à haut risque et les partenariats avec les entreprises locales n'ont pas été pris en compte dans les hypothèses clés de la simulation.

Caractéristiques Expérimentales

Ces sections suivantes décrivent les caractéristiques expérimentales, techniques et d'évaluation des performances du modèle de simulation développé pour la logistique de la ville de Phnom Penh, au Cambodge, orientée vers le PI. La simulation a été mise en œuvre à l'aide du logiciel de modélisation AnyLogic et d'un ordinateur à haute performance, et des indicateurs clés de performance (KPIs) tels que le délai d'exécution, la fonction de coût et l'empreinte carbone ont été utilisés pour évaluer l'efficacité, l'efficacité et la durabilité du paradigme du PI. L'étude de cas porte sur une entreprise de commerce électronique appelée Little Fashion, sur ses défis logistiques et sur les opérations actuelles de sa chaîne d'approvisionnement, y compris la gestion des entrepôts et les livraisons au dernier kilomètre.

Résultats et Discussions

L'expérience a comparé trois scénarios pour les opérations de livraison du dernier kilomètre. Le scénario 2 a donné les meilleurs résultats avec une réduction du délai moyen de 33 %, du délai médian de 55 % et de l'écart-type du délai de 10 % par rapport au scénario 0. Le scénario 2 a également permis de réduire les émissions de carbone de 61 % et était 73 % moins cher que le scénario 0, ce qui en fait l'option la plus favorable en termes de délais, d'empreinte carbone et de coûts d'exploitation.

La mise en place de plateformes locales et de flottes à la demande dans les scénarios 1 et 2 a permis d'améliorer les délais, le scénario 2 affichant une amélioration de 37 % par rapport au scénario de référence. Une réduction significative des émissions de carbone a également été constatée, les scénarios 1 et 2 atteignant respectivement 60 % et 61 % de réduction par rapport au scénario 0. Le scénario 2 a permis une réduction des coûts de 73 % par rapport au scénario 0, soulignant le potentiel de réduction des coûts de la mise en œuvre de hubs locaux et de flottes à la demande. L'étude confirme la faisabilité et les avantages de la mise en œuvre des concepts de PI dans le contexte de la logistique urbaine dans les pays en développement, avec des

améliorations de performance et un impact positif sur les coûts, l'environnement et la qualité du service à la clientèle.

Limites de l'Étude

L'étude de simulation de la logistique urbaine orientée vers le PI présente plusieurs limites : elle est basée sur une seule semaine de données et peut ne pas saisir les tendances à long terme ou les variations de la demande, les hypothèses de trafic sont simplifiées et ne tiennent pas compte des scénarios stochastiques, le modèle repose sur des approximations sans analyse de sensibilité, la simulation est spécifique à une zone géographique particulière et peut ne pas être applicable ailleurs, les facteurs externes et les événements inattendus ne sont pas pris en compte, et la simulation n'inclut pas d'autres indicateurs environnementaux ou sociaux au-delà des émissions de carbone, tels que la pollution sonore et la qualité de l'air, qui sont importants pour la santé et le bien-être de l'être humain.

Chapitre 5

Résumé de la Recherche et Contributions à la Thèse

L'étude de recherche s'est concentrée sur le contexte et les défis de la logistique urbaine dans les pays en développement, en particulier en Asie du Sud-Est. Elle a mis en évidence les problèmes rencontrés par les pays en développement, tels que les embouteillages, l'insuffisance des infrastructures et le manque de fiabilité des véhicules, et a proposé l'utilisation de l'Internet Physique (PI) comme solution potentielle.

Inspiré par (Crainic et Montreuil, 2016), le chapitre 3 a apporté une contribution conceptuelle à la première question de recherche. Ce chapitre a évalué les niveaux d'accessibilité et d'intérêt de chaque concept de PI décrit précédemment et a conclu que les concepts prioritaires pour résoudre notre énoncé de problème devraient être "Partage de l'information et systèmes normalisés", "Activités collaboratives à multiples facettes" et "Interconnexions des parties prenantes dans un système ouvert". Sur cette base, un ensemble de scénarios a été conçu pour mettre en pratique le PI afin d'améliorer la livraison des marchandises dans le contexte de la logistique urbaine dans les pays en développement. Ces scénarios ont été organisés par la mise en œuvre de PI-hubs, de systèmes de transport à la demande et de services, et par le partage des actifs.

Cette étude a formulé trois questions de recherche liées à la mise en œuvre et à l'évaluation des concepts de PI dans les contextes des pays en développement et a exploré les avantages du PI dans la logistique urbaine grâce à l'élaboration de scénarios et d'un modèle de simulation hybride. Les résultats expérimentaux basés sur un cas de logistique du commerce électronique dans la ville de Phnom Penh ont montré des améliorations significatives des indicateurs de performance, y compris le délai de livraison, les coûts logistiques et l'empreinte carbone, avec des économies potentielles allant jusqu'à 75 %. Cependant, l'étude a reconnu les limites et a discuté des perspectives futures.

En résumé, l'étude de recherche a identifié les défis de la logistique urbaine dans les pays en développement et a proposé l'utilisation de concepts de PI pour relever ces défis. Elle a fourni une vue d'ensemble de l'état de la recherche sur le PI, formulé des questions de recherche et

élaboré des scénarios et un modèle de simulation pour évaluer l'impact de la mise en œuvre du PI. Les résultats ont démontré les avantages potentiels du PI pour l'amélioration des indicateurs de performance. Toutefois, les limites ont été reconnues et d'autres perspectives ont été discutées.

Travaux et Perspectives Futurs

Les perspectives associées à ce travail de recherche sont évidemment très nombreuses. Nous distinguerons les perspectives industrielles et les perspectives de recherche.

En ce qui concerne les premières, et même si nous sommes déjà en mesure d'affirmer les bénéfices du PI sur la logistique urbaine dans les pays en développement, il semblerait opportun d'envisager les actions suivantes afin de consolider les recommandations opérationnelles que nous pourrions faire :

- Développer le cas d'application en étendant la période de temps considérée (1 semaine actuellement) et en effectuant des analyses de sensibilité sur tous les paramètres et données du modèle. Il s'agit d'une étape cruciale qui permettra de vérifier et de valider la robustesse des résultats et des recommandations associées pour les praticiens.
- Renforcer le travail de validation des données des cas d'utilisation en travaillant plus étroitement avec les praticiens, notamment sur la pertinence des hypothèses formulées et des données utilisées. Ici aussi, cette étape est importante pour garantir la validité des conclusions de la recherche.
- Étendre les simulations proposées à d'autres cas industriels, en particulier à des entreprises qui ne sont pas issues du commerce électronique. Étant donné que le commerce électronique présente certaines spécificités, il serait intéressant d'envisager d'autres catégories d'entreprises qui peuvent présenter des caractéristiques différentes, nécessiter des solutions différentes en matière de mise en œuvre et obtenir des résultats différents.
- Poursuivre les expériences dans d'autres environnements logistiques urbains (villes d'autres pays par exemple). La plupart des données et des paramètres utilisés dans ce travail de recherche ont été extraits du terrain et sont donc très orientés vers Phnom Penh. Il serait bon de s'assurer que le travail reste cohérent dans d'autres pays en développement au-delà de cette ville particulière.
- Développer un nouveau cas expérimental qui permettra de tester le scénario #3 proposé afin d'évaluer l'impact du partage des ressources sur les indicateurs de performance. Ce cas nécessitera un minimum de deux acheteurs ou plus ayant le même type de clients et situés dans la même ville. Il s'agit d'une perspective majeure car le travail conceptuel effectué a montré la potentialité de ce scénario mais la contrainte de temps pour l'exécution de cette thèse ne nous a pas permis de le vérifier à travers une expérience concrète.
- Envisager des mises en œuvre concrètes sur le terrain inspiré des simulations réalisées afin de finir de valider les recommandations d'affaires formulées. En particulier, une mise en œuvre concrète des recommandations d'affaires développées dans l'étude avec la société Little Fashion, partenaire de ce travail de recherche, semble être une priorité. Nous pouvons imaginer mettre en place quelques PI-Hubs dans les mois à venir dans la ville de Phnom Penh et aussi probablement tester les systèmes de transport à la demande avec quelques-uns d'entre eux.
- Proposer, dans une perspective à moyen terme, un plan de communication à destination des entreprises et des institutions publiques des pays en développement susceptibles de donner une suite opérationnelle à grande échelle à cette étude. Il s'agira d'analyser les implications sociales et économiques de la mise en œuvre des scénarios définis

(notamment 1 et 2), telles que leur impact potentiel sur l'emploi, les entreprises locales et le comportement des consommateurs. Cela pourrait permettre de s'assurer que les solutions proposées sont durables et équitables. Faire connaître les résultats de la recherche scientifique au monde socio-économique est un défi trop souvent négligé.

En ce qui concerne ce dernier point, les conditions dans lesquelles cette thèse a été réalisée ne nous ont pas permis d'explorer pleinement toutes les hypothèses de recherche. En outre, les résultats obtenus ont ouvert de nombreuses pistes pour la poursuite de la recherche scientifique, notamment :

- Examiner beaucoup plus largement comment prendre en compte les spécificités de l'environnement logistique du transport du dernier kilomètre dans les pays en développement. Pour l'instant, notre approche se limite à une approche réaliste mais relativement simpliste (ajuster les vitesses des véhicules en fonction des contraintes géographiques et temporelles par exemple) qui ne prend que partiellement en compte la complexité des facteurs existants. D'autres travaux de recherche ont fait des choix différents pour ce faire. On peut imaginer, par exemple, de simuler ou d'émuler à partir d'une solution de jumeau numérique tous les véhicules d'une ville donnée sur la base des données GPS disponibles.
- Étendre la conception de scénarios aux autres composantes du PI que nous avons mises en évidence dans l'étude. En effet, si notre étude a permis de modéliser les leviers les plus prometteurs de l'IP et a déjà démontré des bénéfices potentiels très importants, de nombreux autres axes potentiels restent à formaliser et à évaluer. Seules 3 des 9 dimensions du cadre que nous avons proposé ont pu être exploitées dans ce travail de thèse et ont généré 3 scénarios orientés PI. Les axes supplémentaires sont donc probablement très nombreux, permettant d'envisager des gains et des réponses aux problèmes de logistique urbaine dans les pays en développement encore plus importants.
- Travailler à l'extension des modèles et simulations proposés afin d'envisager réellement le potentiel de mutualisation et de partage entre les entreprises. Malheureusement, si l'ambition de la thèse était bien d'évaluer le potentiel de l'Internet Physique, force est de constater que les résultats produits se limitent à ce que l'on pourrait appeler l'Intranet Physique, du moins pour les chargeurs. Il manque clairement l'idée directrice du PI qui considère que les chargeurs peuvent et doivent partager leurs ressources et apprendre à mutualiser leurs activités. Cette idée, bien que mentionnée tout au long de la thèse, n'a pas été suffisamment étudiée.
- Travailler à l'optimisation de la réponse aux commandes et des processus dans un contexte de PI. À ce jour, seules des règles de mise en œuvre très simples ont été testées pour soutenir la mise en œuvre des travaux de recherche (FIFO pour le traitement des commandes, chemin le plus court pour les itinéraires des véhicules...). De nombreuses alternatives pourraient être imaginées pour améliorer l'efficacité et l'efficience des scénarios. Des outils scientifiques issus du monde de l'optimisation ou du Machine Learning pourraient être mobilisés à bon escient. Les perspectives sur ce point sont nombreuses et très prometteuses.
- Envisager des indicateurs de performance supplémentaires pour étayer l'analyse des résultats. Bien que nous ayons essayé de proposer une analyse de performance robuste basée sur une perspective de développement durable, elle est actuellement limitée à trois indicateurs relativement simples. D'autres dimensions de la performance pourraient être envisagées pour améliorer la qualité de l'évaluation des avantages et des inconvénients des solutions proposées. En particulier, des indicateurs sur la dimension sociétale seraient les bienvenus, et la partie relative à la mesure de la qualité de service pour les

clients pourrait être fortement enrichie. Il faut également noter que la fourniture de ces indicateurs nécessite l'accès à des données de base qui doivent être cohérentes pour garantir la pertinence des résultats (coût au kilo/kilomètre, par exemple). Ces données ne sont pas toujours facilement accessibles et sont particulièrement volatiles. Un travail de consolidation de la qualité de ces données pourrait également être mené.

- Étudier l'extension de l'approche au reste de la chaîne d'approvisionnement (approvisionnement, production, entreposage...) afin de ne pas limiter l'utilisation potentielle du PI aux livraisons finales. C'est une évidence, mais les problèmes logistiques des pays en développement ne se limitent pas aux livraisons du dernier kilomètre. Si nous avons choisi de nous concentrer sur ce problème spécifique dans le cadre de cette étude, l'approche proposée pourrait être ouverte au reste de la chaîne d'approvisionnement sans difficulté. Les applications à la logistique interurbaine, à la logistique de l'import-export ou à l'approvisionnement sont également des questions très importantes dans les pays en développement.

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Dear Father,

Please rest in peace. I have now finished my PhD.

LIST OF ABBREVIATIONS

ABM Agent-Based Modeling

ALICE Alliance for Logistics Innovation through Collaboration in Europe

ALICE-ETP Alliance for Logistics Innovation through Collaboration in Europe, European Technology Platform

C Customer

CBDs Central Business Districts

CL City Logistics

Customer ID Customer Identification Number

DES Discrete-Event Simulation

DI Digital Internet

DPWT Department of Public Works and Transport

DTI Delivery Technology Innovation

FIFO First-In, First-Out

FMCGs Fast-Moving Consumer Goods

GDP Gross Domestic Product

GIS Geographic Information System

GNI Gross National Income

GPS Global Positioning System

HDI Human Development Index

IMF International Monetary Fund

IoT Internet of Thing

IT Information Technology

JICA Japan International Cooperation Agency

KPIs Key Performance Indicators

L Local Hub

LPI Logistics Performance Index

LTL Less than Truckload

LSPs Logistics Service Providers

M Main Hub

OECD Organisation for Economic Cooperation and Development

List of abbreviations

| | |
|---------|---|
| OLI | Open Logistics Interconnection |
| PI | Physical Internet or π |
| PIOCL | PI-Oriented City Logistics |
| PIOCLDC | PI-Oriented City Logistics in Developing Countries |
| PPUTMP | Project for Comprehensive Urban Transport Plan in Phnom Penh Capital City |
| RHAs | Ride Hailing Apps |
| RQs | Research Questions |
| SC | Supply Chain |
| SCM | Supply Chain Management |
| SD | System Dynamics |
| SLR | Systematic Literature Reviews |
| STD | Standard Deviation |
| SUL | Smart Urban Logistics |
| TESTI | Transport Expert Survey Team Initiative |
| UN | United Nations |
| UNCTAD | United Nations Conference on Trade and Development |
| UNDP | United Nations Development Programme |
| UNICEF | United Nations International Children's Emergency Fund |
| VOC | Vehicle Operating Cost |
| VRP | Vehicle Routing Problems |
| WB | World Bank |
| WEF | World Economic Forum |
| WESP | World Economic Situation and Prospects |
| WFP | World Food Programme |
| WHO | World Health Organization |
| WHR | World Health Report |

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INTRODUCTION

As a citizen of a developing country, my desire in starting this doctoral work was to be able to contribute to the progress of my country. As a researcher in logistics, my ambition was to contribute to help better moving goods between suppliers and customers of developing countries urban areas.

Let's imagine for a moment that you are a parcel that needs to be delivered to a customer who wants or needs you as quickly as possible. If you're moving to Paris, Chicago or London, it should be easy, but if you're moving to Phnom Penh, Abuja or Caracas, it is likely to be much more complicated. In fact, the context of urban logistics in developing countries is very different from that in developed countries. There are huge traffic jams, poor infrastructure, no real traffic laws, old vehicles, high pollution, little public transport and many other critical features. You will probably get lost, waste a lot of time, money and fuel getting from one place to another, and risk arriving late and being damaged. And by the way, I advise you to be very careful when you decide to cross the road in a city like Phnom Penh because I don't want to lose you in a traffic accident. I am serious. The United Nations recently reported that traffic accidents kill and injure far more people in cities in developing countries than in developed countries...

Could we raise enough money to invest in new infrastructure and systems to solve this situation? Probably, yes. But it will take a very, very long time and a lot of money to be effective. And you, as a package, need to be delivered today to your customer... You can't afford to wait decades for better logistics. That's why I'm not really convinced by this option...

One alternative is to use our existing resources more efficiently. Cities in developing countries are full of potential and already available resources that could probably be better used. Think of all those tuk-tuks in Phnom Penh, for example, that wait for passengers for hours when they could probably also be used to deliver goods during off-peak hours. Whether it is vehicles capable of transporting goods (motorcycles, cars, tuk-tuks, vans...) or information and communication technologies, there are many possibilities to transport better with what we have.

Our idea is to support this approach with open and transparent asset sharing and flow consolidation. This is also the ambition of the Physical Internet. This is why in the rest of this document; we propose to study the potential of the Physical Internet to improve the performance of urban logistics in cities of developing countries.

CHAPTER I. CONTEXT AND PROBLEM STATEMENT

“I think frugality drives innovation, just like other constraints do. One of the only ways to get out of a tight box is to invent your way out.”

~ *Jeff Bezos, founder of Amazon, April 2008.*

Logistics today is not environmentally and socially sustainable for both developed and developing countries. There are more and more challenges regarding freight transportation of the first and last mile deliveries, mainly in cities, as, congestion, emission and cost (Crainic & Montreuil, 2015). To reach the target of this new supply chain ecosystem and notably to improve the performances of city logistics' activities, researchers and practitioners have to cope with problems differently for the specific contexts of developed or developing countries (Arvianto et al., 2021). In its study, and particularly in its Chapter, we will make a specific focus on the developing countries' issues.

The main goal of city logistics is environmentally friendly and sustainable living by reducing the negative impact of freight-vehicle movements, particularly on our city-living conditions, for instance, congestion/mobility and environmental impact (Cortés-Murcia et al., 2022; Kim et al., 2021). Improvements are expected to become more sustainable in such a context and both scholars and practitioners are working hard to develop new methods, approaches, tools, and technologies able to contribute to this goal (Cortés-Murcia et al., 2022; Grest, 2022; Kim, 2021; Treiblmaier et al., 2020).

However, most of these proposals are designed by and for developed environments, and particularly developed countries (Arvianto et al., 2021; Cortés-Murcia et al., 2022). While developing countries have also huge challenges to solve in the matter of supply chain, logistics, and transportation (Arvianto et al., 2021). As a consequence, it seems imperative to start studying the properties and challenges of city logistics for developing countries to notice if they are similar or different from their developed counterparts. This is the purpose of this first Chapter.

1. General Features of Developing Countries

Talking about developing countries means discussing several cases, several levels of development, and geographies, where the term brings together many different situations (World Bank, 2022c). This section explains the general features (e.g., definition, properties, business typology, etc.) at different stages of development of developing countries. Subsequently, we will specifically focus on Southeast Asian developing countries, which is the main application area of this research work. Common features in problems and solutions of developing countries will be considered and classified in this study.

1.1. Overview of Developing Countries

Several classification schemes are used to categorize countries as developed or developing. Various organizations have used many factors for analysis purposes to classify and rank countries, such as national income, human development, and growth rate. Typically, the United Nations (UN) uses the UN Human Development Index (HDI), which is a summary measure of the average achievements in key aspects of human development (United Nations, 2022). The HDI emphasizes that people and their capabilities should be the ultimate criteria for assessing the development of a country, not economic growth alone (United Nations, 2022). HDI divides into four groups: low (0.385-0.549), medium (0.550-0.699), high (0.700-0.799), and very high (0.800-0.965). Generally, the HDI of developing countries is 0.685 or below (UNDP, 2022). According to the country classification system of the United Nations Development Programme (UNDP), the HDI is made up of three metrics that evaluate a country's performance: longevity, education, and income. This is done to capture the multifaceted nature of development.

Figure. 1 presents a world map of countries classification following the HDI criteria.

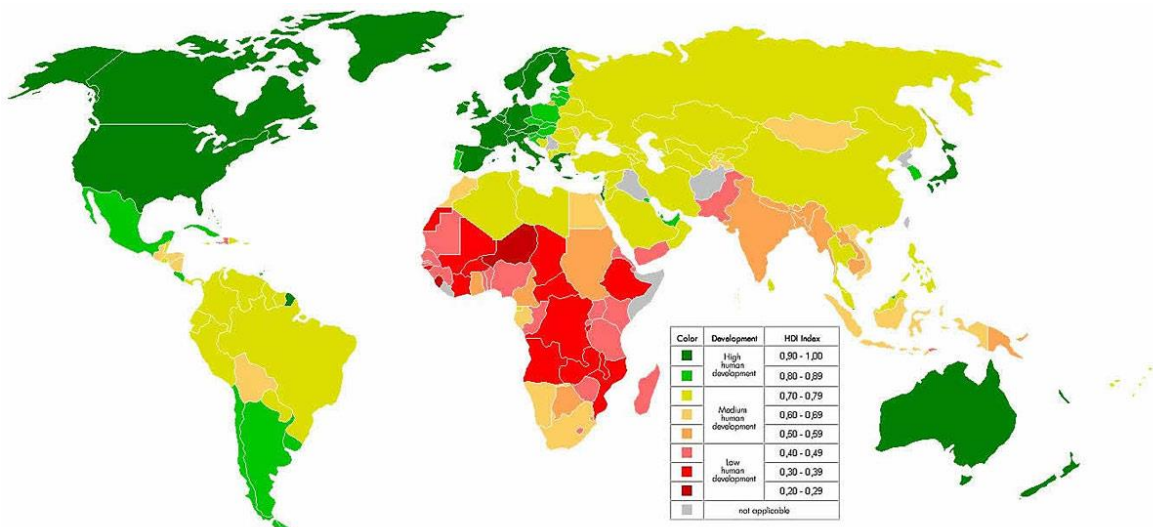


Figure 1: World map of Human Development Index (United Nations, 2022).

Other dimensions of development, such as political freedom and personal security, and of course the income per capita have been identified as critical (Nielsen, 2011, 2013). For instance, the World Bank (WB) uses the gross national income (GNI) per capita for this form of classification (World Bank, 2023b). Similarly, the World Economic Situation and Prospects (WESP) report divides all countries into three broad categories: developed economies,

economies in transition, and developing economies. These countries have been classified by their level of development as measured by the GNI. The threshold levels of GNI per capita are those established by the WB to maintain compatibility with similar classifications used elsewhere (United Nations, 2022). For the current 2023 fiscal year, low-income economies are defined as those with a GNI per capita, calculated using the World Bank Atlas method, of \$1,085 or less in 2021; lower middle-income economies are those with a GNI per capita between \$1,086 and \$4,255; upper middle-income economies are those with a GNI per capita between \$4,256 and \$13,205; high-income economies are those with a GNI per capita of \$13,205 or more (World Bank, 2023b).

Besides, it is difficult to identify a common and unified definition of developing countries (C. Gordon, 2012). (Fantom & Serajuddin, 2016) found that the use of GNI per capita is still a practical and reasonable method to categorize countries for analytical purposes. This current approach corresponds well with many accepted criteria for development outcomes, particularly rankings. Thus, the income classification is widely used within and outside the WB for comparing attributes between groups of countries. In our study, we decided to consider developing countries as all countries listed in the WB's classification system, released in 2022, as low and lower/upper-middle income countries (World Bank, 2022b). This is similar to classification schemes used by other international organizations like the International Monetary Fund (IMF) and the UNDP, which refer to "emerging and developing countries" and "developing countries" (Abdi & Lamíquiz-Daudén, 2022).

These countries share some characteristics in general, such as large young populations, megacities with fast urbanization, poor infrastructures, gradually increasing economies, and transportation-related externalities (Pojani & Stead, 2017). According to (Agarwal, 2022), there should be consideration of five common characteristics of developing economies: (1) low per capita real income, (2) high population growth rate, (3) high rates of unemployment, (4) dependence on the primary sector, and (5) primary commodity export dependence. Essentially, developing countries should be defined through a set of 4 major categories of features described as followed Figure. 2:

- **Revenue development:** Low income per capita and low standard of living;
- **Business development:** Substantial dependence on primary sector and agricultural production, low productivity and limited opportunities for employment;
- **Social development:** High population growth, poor health and education, inequality, corruption, poor safety and security;
- **Land development:** Poor infrastructures and strong urbanization.



Figure 2: General features of developing countries

1.2. Context of Southeast Asian Developing Countries

As our study has been mainly focused on this region, let's have a specific look on the Southeast Asia countries. This region is composed of eleven countries of impressive diversity in religion, culture and history. Those eleven countries are Brunei, Myanmar (formerly Burma), Cambodia, Timor-Leste, Indonesia, Laos, Malaysia, the Philippines, Singapore, Thailand, and Vietnam. Additionally, India, Bangladesh, and some regions of China are usually considered as a part of this area. Basically, and according to the previous criteria discussed, they can all be considered as developing nations. Two notable exceptions are Singapore and Brunei as they are clearly developed countries notably due to their advanced technologies and infrastructures (Kamarudin et al., 2022). The developing economies of Southeast Asian countries are shown on the map on the two following Figures 3 and 4 (World Bank, 2022d). We can notice that Malaysia and Thailand have successfully diversified their economy and made remarkable progress in social and economic development. As a result, both are considered now to be upper-middle-income countries (World Bank, 2022a, 2022d). Malaysia is expected to achieve its transition from an upper middle-income economy to a high-income economy by 2024. The Figure 3 and 4 below shows that other countries of the Region continue to get a very low GDP per capita (under \$4000).

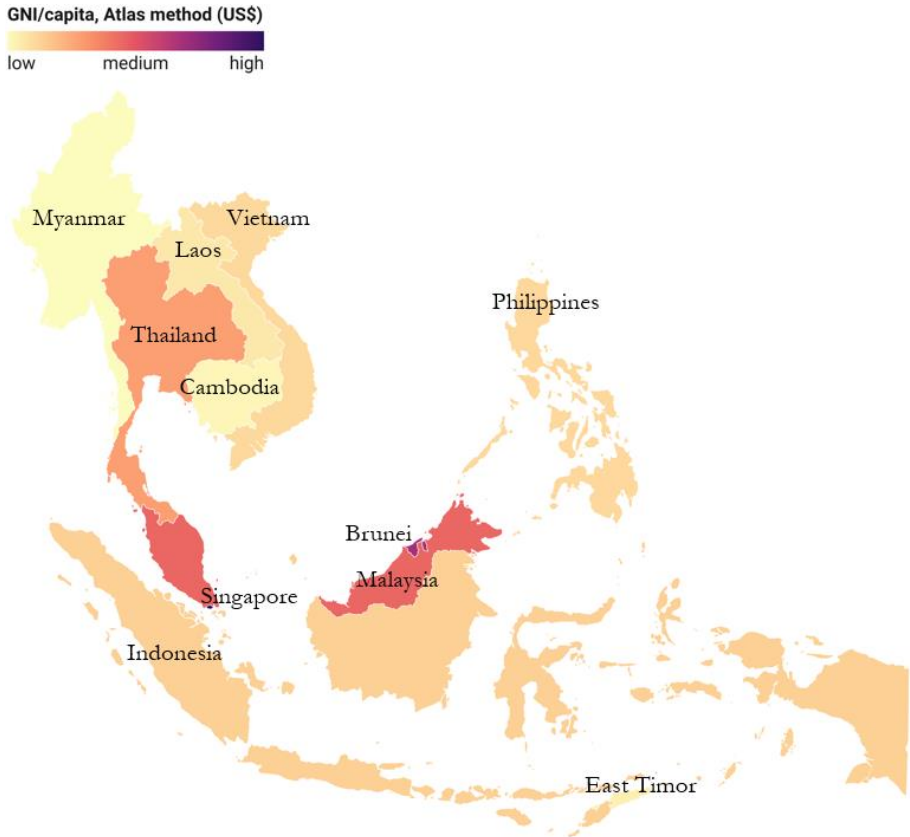


Figure 3: The developing economies of Southeast Asian (World Bank, 2022a)

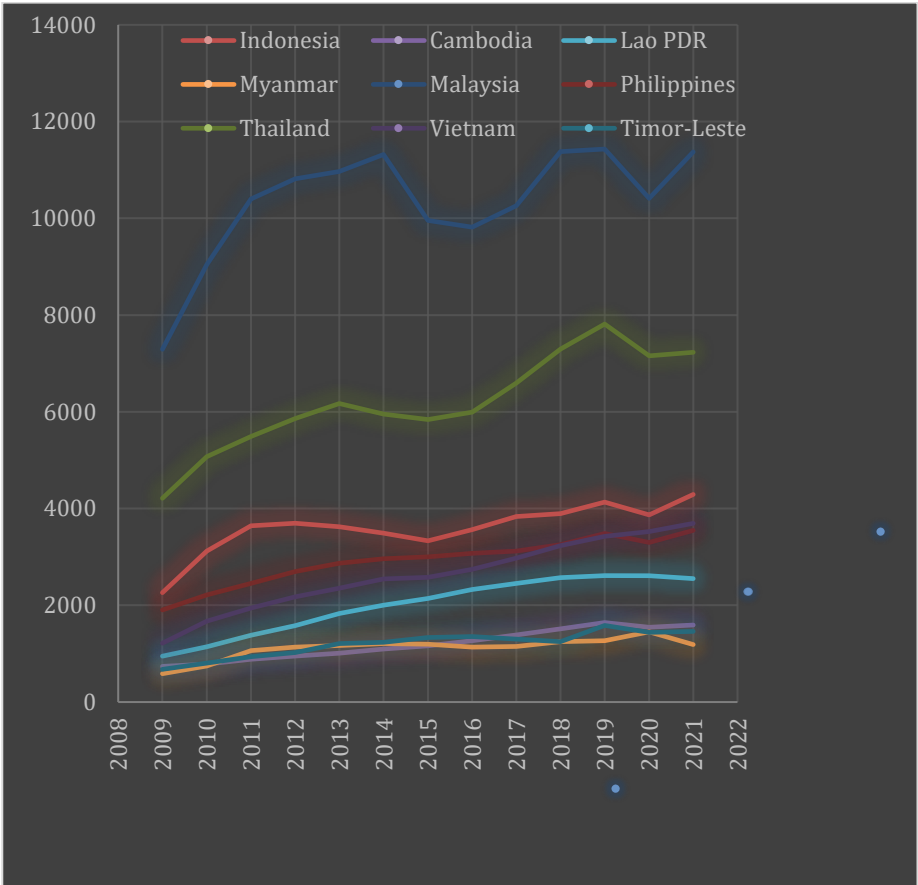


Figure 4: GDP per capita in US dollars of Southeast Asian developing countries from 2009 – 2021 (World Bank, 2022d)

Finally, this part of the world is at the centre of major challenges such as climate change, agriculture and food security, education and health development, energy production and distribution, environment preservation, funding and governance and social development. In addition, as far than more than half of the Southeast Asia population lives in urban area and as a billion more people should join them in the next 30 years (World Bank, 2022c), the question of infrastructures and transportation will be particularly challenging. IMF and WB estimated recently that this part of the world will need \$1.7 billion a year for improving their infrastructures just to maintain growth and tackle climate change impacts. More than 30% of this amount will be in city transport infrastructures and means. In such a context, the question of a better management of freight and passenger transportation in urban areas seem to be of prime importance.

2. Developing Countries' Challenges

In this part, we will go into more details about the main challenges of developing countries and will make a specific focus on the southeast Asian ones. To do so, we will consider the four categories of features defined on Figure 2.

2.1. Revenue development challenges

In 2001, the international community deemed a yearly growth rate of at least 7% necessary to eradicate poverty in developing countries and put their economies on a path of accelerated growth and sustainable development. This goal was also introduced in 2015 in the 2030 Agenda for Sustainable Development of the UN, under target 8.1 of the Sustainable Development Goals.

Despite large differences in growth performance among these countries, the United Nations Conference on Trade and Development (UNCTAD) revealed in 2019 the extent to which the 7% growth target was unreachable for most of them. In addition, the COVID-19 pandemic and the Ukrainian War have made the situation considerably worse (UNCTAD, 2022).

Basically, according to UNCTAD and WB, the progress made to enable developing countries to move towards the 7% graduation was inadequate (UNCTAD, 2022). Low productive capacities, limited economic diversification, dependence on natural resources and high trade costs remain among the major obstacles they face to achieving sustained economic growth and development (World Bank, 2022c).

From 2001 to 2010 already, only 15 out of 46 least developing countries attained the target growth rate, while 10 suffered a strong contraction in real GNI per capita. In the early 2010s, the situation started to deteriorate progressively under the international objectives as commodity prices began to slide. The divergence between the concerned countries became more and more pronounced after 2016, and especially after the COVID-19 pandemic. UNCTAD analysis shows, for example, that it could take five or more years for one third of developing countries to recover to their already low pre-pandemic levels of GNI per capita. In 2020, the median annual GNI per capita for developing countries was between \$905 and \$3,970, comparing to \$24,085 for developed countries (World Bank, 2023a).

Given the number of developing countries suffering real declines in GNI per capita, the growth record of the last 20 years represents a strong reminder of the vulnerability of the world's poorest countries to boom and bust cycles, such as those observed in commodity markets (UNCTAD, 2022). According to (World Economic Forum, 2022), the most important global challenges for the future of developing countries should be summarized along two main axes: global economic risks and the preservation of social cohesion. While there is no easy or standard solution for facing and minimising such risks, today's developing countries' economies continue to need to account for such challenges.

2.2. Business development challenges

Agriculture is crucial to economy and counts for 4% of global gross domestic product (GDP) and in some least developing countries, it can account for more than 25% of GDP (World Bank, 2022c). Yet their agricultural production for domestic and export markets has lagged behind,

with per capita output growth declining since the 1990s. Yet their agricultural production for domestic and export markets has lagged, with per capita output growth declining in the 1990s. Slow production growth and large annual fluctuations in output have remained chronic problems for developing countries, constituting the main causes of their persistent poverty and growing food insecurity. Climate change also contributes largely to these difficulties.

In terms of trade, developing countries have continued to be marginalized in world agricultural markets, accounting for only 5% of world agricultural exports in the early 1970s and barely 1% in the early 2000s (WFP, 2020)... The poor performance of developing country agriculture is linked to the many internal and external challenges that these countries face in developing the sector and achieving their goals. Their internal challenges include low productivity, rigid production and trade structures, a limited skills base, low life expectancy and educational attainment, poor infrastructure, and inadequate institutional and policy frameworks (World Bank, 2022c).

If manufacturing has been the surest way for developing countries to reduce poverty and create jobs, these countries are now turning to the service sector, and notably e-commerce businesses, to catch up with their developed counterparts (World Bank, 2022c). Countries at all levels of industrialization and income can exploit the transformative potential of services. More and more governments and businesses in the developing world are working to eliminate obstacles to the adoption of new technologies and their associated businesses. In terms of Internet use, for instance, developing countries continue to grow faster than developed countries (UNCTAD, 2022). This fact provides a reasonably good indication of whether the foundations of a "digital economy" exist in developing countries. Internet-based economic structures and information groups are the new business reality, as organizations and individuals revel in the ease of purchasing commodities and services from foreign shores. If most developing countries were still far from experiencing this reality due to many factors which act as obstacles for e-commerce, (Alyoubi, 2015), over the past three decades, the services sector has grown faster than manufacturing in many developing economies. By 2019, services accounted for 55% of GDP and 45% of employment in developing countries (World Bank, 2022c). The economic transformations driven by services offer new opportunities for scale, innovation, and ripple effects of similar magnitude to those that have made manufacturing more productive in the past. Remote delivery, branching, and franchising allow service providers to tap into larger markets, and providers who offer digital services are no longer limited to face-to-face engagements with their customers. Digital technologies are improving business processes, introducing new product features, and creating new markets (World Bank, 2022c).

2.3. Social development challenges

The world's total population increased by almost 1 billion persons per decade since the eighties up to more than 8 billion now, with approximately 86% of this growth to take place in the cities and towns of developing countries (Montgomery, 2008). Developing countries are those with the highest population growth. Based on the global population record recently, Asia (59.6%) and Africa (17.5%) have the largest share of the world's population (World Bank, 2022c). This trend is not about to stop, as UN forecasts estimate that the African population will increase fourfold by 2100. This growth is due to high fertility combined with low mortality in Africa and Asia. This number will be the fastest population growth in history (Montgomery, 2008).

This growth is also met with rising inequality, stresses on social cohesion and demographic pressure, led by a relatively faster growing number of youth than older cohorts searching for jobs, fast and unmitigated urbanization, and international migration as a response to the search for a better life (Alvaredo et al., 2017).

Developing countries also need to deal with eroding trust in government, notably due to important corruption (OECD, 2019). This has recently included rising skepticism of globalization, particularly amongst the middle class. While technological change is a likely factor in this sentiment, as it was in the early industrial age, a general negative feeling against trade imports and foreign direct investments, as primary reasons for job insecurity and inequality, often prevails (OECD, 2019).

Last but not least, Health and Education issues are key features of the developing countries' status. Today, the number of educated people in the world is higher than ever. In 1820, only 12% of the world's population could read and write. Today, the proportion is reversed. However, these figures hide the impact of persistent inequality. Some 63 million primary school-age children were not in school in 2016, and progress in primary school enrollment remains stagnant (The Human Journey, 2022; UNICEF, 2023). The most impacted are developing countries, where the lack of basic education is a harsh constraint on development. In Niger, for instance, only 36.5% of 15- to 20-year-olds are literate (The Human Journey, 2022). According to the World Bank's 2018 report (World Bank, 2018), rising school enrollment does not mean that all of these children are getting a good education. Globally, 125 million children do not achieve functional literacy or numeracy, even after four years of schooling. Poverty and inequality are certainly factors, both between and within countries. In developing countries, the average student performs worse than 95% of students in wealthier OECD countries (OECD, 2022). Many factors undermine the effectiveness of schools in developing countries. Chronic malnutrition, disease, and chaotic or violent environments compromise children's early development. Quality teachers-indeed, all teachers-are scarce. School management is often weak, and the availability of resources cannot always keep pace with rapidly increasing enrollment.

The 2000 World Health Report also pointed out three fundamental objectives of health systems, namely improving the health of the populations they serve, responding to people's expectations, and providing financial protection against costs due to illness (WHO, 2000). In addition, it stressed the poor's need for financial protection being as great as or greater than well-off people, since even small absolute risks may give birth to catastrophic consequences for the poor. In 2017, 6.3 million children and teenagers died, including 5.4 million in the first five years of life, mostly from easily preventable diseases (UNICEF, 2019). Most of these deaths occur in sub-Saharan Africa and South Asia, basically in developing countries. A child born in one of these two macro-regions is up to nine times less likely to survive the first month of life than a child born in a developed country (Mango, 2020). One element that contributes to the severity of the health crisis is the imbalance between needs and institutional responses. Many factors complicate the construction of effective public health systems: new health centers cannot be established without sufficient equipment, supplies, and personnel to provide basic services. The number of doctors is insufficient (Africa has only 3% of the world's health workforce). While the poorest countries bear the brunt of 85% of the global burden of disease, they account for

only 11% of global health spending, yet have the need to develop more resilient and efficient health systems (Mango, 2020). The main problems of health systems in poor countries therefore seem to lie in the shortage of health workers. World Health Organization (WHO) estimates that 27 countries in Africa and Asia are short at least 4.3 million health workers (WHO, 2022). The global shortage of health workers is a major concern for many countries. The global shortage of health workers and its impact, as well as the high number of people (more than 100 million) who become impoverished each year by paying out-of-pocket for health care, are creating real health system failures (Mango, 2020). Solving these problems requires an effort and investment to improve public health systems, which can guarantee access to necessary services, especially for the poorest and most vulnerable people. The issue of health is linked to many issues central to people's lives, starting with the construction of local food systems that guarantee access to a diverse and nutritious diet (Mango, 2020).

2.4. Land development challenges

The WB reports in 2022 that in developing countries, most of the population is continuing to migrate to the cities (World Bank, 2022c). Therefore, worldwide, the urban population which was about 55% in 2019, is now estimated to be 60% in 2030 and 70% in 2050 (World Bank, 2022c). Inhabitants are then concentrated in cities, and the share of the urban population is drastically increasing. In India for instance, the urban population has increased from 81 million in 1960 to 471 million now (World Bank, 2022c). So, the total population has increased by 300%, while the urban population has increased by 580 %. In developing countries, the high population growth coupled with an attraction for cities is causing many challenges for economy, facilities and services which are not able to follow accordingly (World Bank, 2022c).

This rapid urbanization of developing countries is particularly impacting in Southeast Asia. For instance, with an annual growth rate of 3% of its urban population, Vietnam has the highest rate of urbanization of the region (Ha et al., 2019). Basically, the population increases by approximately 200,000 people each year in Hanoi city and the overall Vietnamese urban population is expected to outnumber the rural population of the country by 2039 (United Nations, 2022).

As they are significant inconsistencies in matter of demographic distribution in suburban and urban areas of developing countries, this strong urbanization movement of developing countries leads to serious troubles in terms of traffic congestion and safety (Amrapala & Choocharukul, 2019; Huu & Ngoc, 2021). (Kitamura et al., 2018; Matsuoka, 2018) firmly reported that in urban areas of Southeast Asian countries, pedestrians and vehicles use the road chaotically. Several studies of (Agustin, 2019; Kitamura et al., 2018; Matsuoka, 2018; UNDP, 2021; Widyanti et al., 2020; Yoshida & Koyanagi, 2018) indicated that road user behaviour is the main reason of urban traffic issues in developing countries. Different types of vehicles, mainly motorcycles (Janstrup, 2017; Truong et al., 2020), operate and navigate differently, resulting in inefficient flow and even dangerous traffic circumstances. Road users, including drivers and pedestrians, frequently disobey traffic rules and guidelines. For example, alcohol and drug use, speeding, regular lane changes, and talking on the phone while driving are major factors in traffic accidents. It is not uncommon to see a driver or motorcyclist ignore a red light when there is no traffic at the intersection or junction. Sometimes they drive on the wrong side of the road and back up to

take a shortcut. The yield sign is not enforced and the yellow boxes at some intersections warning not to stay in the intersection are often ignored (Matsuoka, 2018).

Due to the increasing urbanization already mentioned, the demand for good infrastructure is increasing and expected to soar further. Basically, infrastructure is the backbone of any country as it generates jobs, boost economic growth and improves the quality of life. However, when developing countries' governments push back on certain infrastructure plans, it comes at an enormous social and economic cost. Roughly, 663 million people lack access to clean water, 2.4 billion people do not have adequate sanitation, one-third of the world's population is not served by an all-weather road and over 1.1 billion people, or almost 16 percent of the world's population, still have no access to electricity (WHO, 2019). In recent years, many developing countries have been scaling up infrastructure investment, mostly through public spending, but also with a growing participation of the private sector. These recent improvements have had a significant impact on reducing these and other problems in developing countries. Mobile services, for instance, have spread rapidly and have allowed people to join the global information age. In 2016, 85% of people in developing countries were covered by a cellular signal which represents a huge. Transportation services also drive economic development and generate wealth and employment (The Borgen Project, 2022). However, there is evidence that infrastructure developments of developing countries will need several decades and billions of dollars to be achieved. Particularly in a context where the developing countries' infrastructure policy is biased toward the realization of new investments at the detriment of the maintenance of the existing stock. As a consequence, developing countries will continue to suffer from their deficit in matter of infrastructures for a long time.

This is particularly true for transportation infrastructures although they are key to development. They allow wealth, equality, and well-being and are crucial to any nation, let alone to less developed countries. In the developing countries, where most people do not own a car, improved public transport is essential for economic growth and a good quality of life. These infrastructure investments reduce bilateral transportation costs between connected locations, which has direct effects on the spatial distribution of economic activity through three main channels, lowering the costs of: (i) trade in goods; (ii) population migration; and (iii) commuting (Redding, 2023). The impact of infrastructure investments is typically amplified by agglomeration forces, i.e., the benefits that arise from the geographic clustering of people and firms. Unfortunately, many developing countries often lack the resources to effectively plan and implement essential transport projects (The Borgen Project, 2022).

3. The City Logistics Challenges for Developing Countries

In this section we are focusing on the logistics challenges that developing countries' cities have to manage. Notably, we will discuss the concept of city logistics in general before studying these activities in the specific context of developing countries. Finally, we will share some insights regarding the particular case of Phnom Penh City which will be used as an experiment field for this research.

3.1. The City Logistics concept

City logistics or urban logistics is usually defined as all freight transportation activities in a city, which covers the review, planning, maintenance and improvement of logistics operations. Every city needs a well-planned city logistics system in order to be competitive within the framework of sustainability principles (Büyüközkan et al., 2022; Büyüközkan & Ilıcak, 2022). Other authors such as (Crainic et al., 2009) indicate that city logistics aims to reduce the nuisances associated to freight transportation in urban areas while supporting their economic and social development. This implies the coordination of shippers, carriers, and movements as well as the consolidation of loads of several customers and carriers into the same environment-friendly vehicles. City logistics explicitly aims to optimize such urban transportation systems (Crainic et al., 2009).

As there is a clear lack of efficiency of city-logistics operations, both from an economic and environmental perspective, numerous scholars and practitioners have developed a lot of works during the last decades. Some literature review studies in the field of city logistics have been produced recently such as (Anand, Quak, et al., 2012; Anand, Yang, et al., 2012; Dolati Neghabadi et al., 2019; Feldman-Savelsberg, 2016; W. Hu et al., 2019; Lagorio et al., 2016). They identify numerous trends and gaps in this sector. (Lagorio et al., 2016) and (W. Hu et al., 2019) notably conducted citation network analyses to highlight the most discussed topics:

- Urban consolidation centers, proximity stations, hubs and lockers;
- Autonomous vehicles in urban mobility and logistics;
- E-commerce related last mile logistics;
- Smart urban-logistics (integration of advanced technology);
- Vehicle Routing Problems;
- Delivery Technology Innovation.

These authors count more than 300 papers published on the last 30 years on that topic, with an important acceleration during the last decade. Unfortunately, almost all these research works have been dedicated to developed countries as stated by (Arvianto et al., 2021). City Logistics issues for developing countries remain poorly studied.

3.2. City Logistics in developing countries

Although not very prolific, (Arvianto et al., 2021) studied the dynamic in city logistics research for developing countries. These have mainly focused on infrastructure to overcome challenges relating to city logistics and urban transportation. Some studies examined the shipping operation zone, urban transportation network, and distribution centres. Meanwhile, very few studies addressed vehicle routing, traffic management, and delivery technology for this specific

environment. Basically, there are more proposals related to the design time of developing countries' city logistics than for the run time.

(Arvianto et al., 2021) also confirmed that the three foremost urban logistics challenges for developed and developing countries are urban population growth, environmental challenges, and traffic congestion. Nevertheless, their literature analysis also demonstrated that developing countries have to cope with additional very specific challenges.

With respect to internal factors, developing countries have not yet introduced advances in logistics operations, unlike developed countries, which have automated vehicles, electric automobiles, and robots. Research works like (Hye et al., 2020; Liu, 2017; Ul-Hameed et al., 2019) studied the consequences of the low performance of city logistics activities in developing countries. They highlighted that the main issues came from weak capabilities regarding both human and machine means, poor track & trace systems and poor innovative and collaborative approaches. Developing countries also continue to rely on conventional vehicles, using mainly light or medium vehicles as shown on Figure 5 (Phun, 2018). These differences instigate the development of different solutions from the ones existing for developed countries. Particularly, this implies a delay in the adoption of technological changes, such as the use of more appropriate logistics distribution vehicles, at least regarding the developed countries' standards.



Figure 5: Unique and typical transport modes in Southeast Asian (Phun, 2018)

With respect to external factors, the classical challenges found for developed countries are lack of education, regulation, network accessibility and capacity, and the emergence of new business models as e-commerce while increasing fleets and insufficient loading/unloading space are common logistics challenges generally addressed in developing countries. The systematic literature analysis made by (Arvianto et al., 2021) about city logistics in developing countries also confirmed that numerous cities are concerned with a huge increase of vehicle numbers. This affects urban freight capacity and frequency, urban delivery time, regulatory enforcement difficulty, and distribution operations. Optimal location of freight networks and facilities, such

as determining the location of warehouses, evaluating distribution centres and regional distribution centres, and evaluating the best network using a candidate distribution centre are the most frequent models and solutions adopted to address infrastructure problems in developing countries. (Arviato et al., 2021) also noted that developing countries have not adopted yet innovations in delivery technology to establish an efficient and optimal distribution process. Another report by (C.-C. Yang & Chang, 2019) indicates that the most important factor affecting the logistics processes of African countries was limited information integration, poor infrastructures, and specific local country risks such as corruption. As shown by (S.-L. Chen et al., 2016), around 98% of material flows in developing countries like Malaysia highly depend on the road while infrastructures are generally not good. On their side, (Kavirathna et al., 2018) revealed that the port of developing countries such as Sri Lanka was lower performance of transshipment hub ports comparing to developed countries like Singapore or Netherlands. All these situations caused several issues by leading to increase cost of logistics, CO2 emission and transport time and to decrease service quality to end-customers (S.-L. Chen et al., 2016). At last, no literature has apparently discussed the disruption of urban delivery networks in developing countries, yet very impacted during the recent crises (COVID-19, Ukrainian war, etc.). To conclude, developing countries city logistics activities do not seem to be effective.

Additionally, other studies demonstrated that developing countries have some issues regarding the efficiency of their logistics activities, particularly in cities. For instance, (Karim et al., 2018) introduced the top three factors impacting warehousing process efficiency which were labour productivity, warehouse utilization and inventory space utilization. Most of the time, logistics plants (i.e., hubs, cross-docking platforms, warehouses, fulfilment or distribution centres) in developing countries are under-used. In parallel, (Dang & Yeo, 2018) pointed out that the position of the country's ranking for Vietnam in the Logistics Performance Index (LPI) fell from 48 in 2014 to 64 in 2016 due to higher logistics costs. This is unfortunately true for most developing countries. As a result, (Dang & Yeo, 2018) noted that one should pay more attentions to the efficiency of logistics service providers (LSPs) and of logistics activities in developing countries. The increase in volume of both people and material flows in developing countries imply that this issue is particularly critical regarding last-mile deliveries and city logistics activities (Rossolov et al., 2019). These growing processes can cause a major problem not only for the cities, but also for the countries. Inappropriate material flows and lack of logistics strategies will cause an increase in the final cost of products and traffic flow deterioration. These will affect to the GDP of countries. Last but not least, researchers such as (Noletto et al., 2017) showed that most of the developing countries did not yet adopt supply chain and logistics networks technologies like Intelligent Packaging or Internet of Thing (IoT). They found that cost and lack of knowledge were the main barriers. This is a questionable situation considering that at a same time people in developing countries are more and more used to live with connected devices such as smartphones.

On the policy side, facility regulation and after-hours delivery were often identified as solutions. Innovative solutions to intangible infrastructure issues including the introduction of green driving programs, collaborative distribution, route planning or trip assignment, fleet management practices with the use of a freight app, and combined delivery, are identified but not really managed for the moment (He & Haasis, 2020). It appears that the research in the developing countries focus on resolving city logistics problems with a short-term perspective.

It implies that public policy and sustainability for city logistics are a potential research avenue to be investigated in developing countries settings, which is supported by (He & Haasis, 2020) who suggested applying long-term perspective in designing city logistics strategies.

To sum up, scholars and practitioners noticed the poor efficiency and effectiveness of city logistics activities in developing countries. However, first research works have been developed recently on that subject with the following concerns:

- Infrastructures: Transport networks, logistics facility location...
- Equipment: fleet size management, packaging...
- Policy: off-hour deliveries, facility regulation, strategy...
- Operations: Vehicle routing problems, collaborative operations, combined delivery system, green driving program, advanced fleet management...

However, this research remains in its infancy and a lot of critical issues are still unresolved.

3.3. The case of Phnom Penh City

Phnom Penh is the main capital city of Cambodia. Several studies (Kitamura et al., 2018; Matsuoka, 2018; Phun et al., 2015, 2018) specified that the rapid urbanization and the traffic issues in Phnom Penh city which were already not good, are becoming worse as shown on the Figure 6 below.



Figure 6: Traffic congestion in Phnom Penh city (Sopha, 2019).

Notably, as the public transportation system of the city is very weak. To manage this issue, the municipality started a decade ago to put up many actions for improving the city transport issues as for instance, the logistics master plan proposed by the Jica project (JICA-PPUTMP, 2014).

Phnom Penh is facing a lot of traffic management issues as stated by the final report of PPUTMP (Phnom Penh City Urban Transport Master Plan), such as: no real public transportation lines, drivers' disregard for traffic rules and regulations, significant parking space shortages, increasing number of vehicles (for passengers and goods), and no pedestrian walking environment and increasing demand for goods deliveries in the city (JICA-PPUTMP, 2014).

The recently proposed city bus model has failed to work in the mixed traffic flow and poor accessibility of Phnom Penh city (Phun et al., 2018). In addition, paratransit (motorcycles, auto-

rickshaws, tuk-tuks, and bicycle-rickshaws) remains very popular and is the main mode of transportation in the urban area, as citizens still prefer door-to-door travel. As a result, the huge majority of Phnom Penh citizens are depending on paratransit services of the city transport (Eung & Choocharukul, 2018; Phun et al., 2015, 2018).

Thanks to the mobile world and wireless communication technology, smartphones through GPS, high-speed internet, and digital route maps have been enabling ride-hailing apps (RHAs) in southeast Asian developing cities. The rapid adoption of these apps has quite considerably impacted passenger movements and last-mile delivery in Phnom Penh. Drivers could enhance their revenue by increasing the number of trips and passengers after implementing RHAs. In recent years, many businesses of RHAs (e.g., PassApp, Tada, Didi, Grab, Easy, Lyft, Uber, and Ola Cabs) have been launched an internet platform to connect clients and transportation providers, help their matching and allow them to interact more effectively. In many cities of developing countries, more RHAs have been improved and expanded to non-fixed route paratransit modes such as motorcycle taxis, taxis, auto-rickshaws, tuk-tuks, and cycle-rickshaws (Phun et al., 2018). By tradition, citizens also continue to hail empty-cruising paratransit on the street or look for it along the streets at a specific pick-up location (e.g., near markets and intersections) (Phun et al., 2018). This tradition tends to die out. Tuk-tuk driving in Phnom Penh is becoming precarious and unreliable due to two main reasons: i) The emergence of home-based transportation apps has increased competition by allowing independent drivers to enter the market and has lowered customers' price expectations. ii) The emergence of "Indian-style" tuk-tuks which is more profitable and used by independent drivers linked to home-based transportation apps (Jack, 2020). In this way, passengers can choose which mode of transportation they want to use, whether it is an Indian-style tuk-tuk or a Khmer-style tuk-tuk. Regarding the cost, the kilometre is a flat fee of 3,000 riels (\$0.75), and each additional kilometre is 1,500 riels (\$0.375). Payment is made in cash to the driver, and the company claims 15% of the profit made, plus 200 riels per trip from the registered driver (Jack, 2020). In addition, paratransit transportation in Phnom Penh modes significantly contribute to social-economic activities due to its service availability and job occasions for low-income household and/or low-skilled people (Phun et al., 2020).

In 2020, the number of registered cars, vans and trucks in Cambodia were around 920,000 while about 5.2 million for the motorcycles. It was only 65,000 for cars, vans and trucks and 200,000 for motorcycles in 1998. Each year, more than 600,000 new vehicles are registered in the country and most of them are used in Phnom Penh City area. This growth occurs also for other categories of vehicles, more specific to developing countries. According to the Department of Public Works and Transport (DPWT), in Phnom Penh city, the number of registered auto-rickshaws increased from 18,030 in February 2018 to 29,288 in November 2018, with Bajajs rapidly growing from 3232 to 14,338; Chinese auto-rickshaws (or Chinese motorized tricycles) slightly increasing from 4659 to 4859, and tuk-tuks (or remarks) remaining unchanged at about 10,000. This pattern noticeably demonstrates Bajaj's increased popularity over competing auto-rickshaw services. Though, many Bajaj drivers did not register their vehicles, according to DPWT. In early 2018, the DPWT, in collaboration with traffic police, enforced and banned unregistered Bajaj drivers from operating, with approximately 200-300 unregistered Bajajs discovered per week (Phun et al., 2020). However, the number of motorcycle taxis (motodops) remains unknown since there is no formal control and record over the operations of motorcycle

taxis (e.g., license and registration). In Cambodia, anyone who owns a motorbike has the option of becoming a motorcycle taxi driver (Phun et al., 2017, 2018).

It is important to notice that a significant part of all those vehicles is also used for goods transportation. However, in Phnom Penh, such as in many other developing countries' cities, companies use their own and dedicated fleet of vehicles to support their freight deliveries.

Because of the unavailability of parking spaces, the practice of sidewalks is frequently used as reserved parking areas for businesses (i.e., shops, restaurants, stores) or customers visiting businesses. As with these existing circumstances, there is no or very few available spaces for pedestrians along many streets in Phnom Penh. So, pedestrians are compelled to walk carriageways, exposing themselves to the traffic stream owing to a lack of parking space. Lack of parking space contributes to traffic congestion by significantly reducing the road's operational capacity. Therefore, parking management is one of the most critical and urgent traffic management tasks in Phnom Penh (Matsuoka, 2018).

(Phun et al., 2017) showed at least five benefits from the integration between smaller-size paratransit system and mass transit transportation system. First, paratransit provides more convenience and easy accessibility to intermodal passengers and improves connectivity between modes. Second, paratransit would be useful for the last mile solutions in an urban area to develop and fix the transit system regarding collection/distribution of passengers from/to the stop points or stations. Third, feeder service could encourage both paratransit and mass transit ridership. Fourth, paratransit provides a cost-effective and high-quality service to meet the transportation demands of the broader public. Fifth, paratransit operators continue to have job prospects (Phun et al., 2017; Phun & Yai, 2016a, 2016b)

4. Thesis Problem Statement

The logistics performance of developing countries is difficult to measure due to lack of data, but approximations made by the WB indicate that these countries are consistently below the average of the global logistics performance index (Kraay, 2018). Overall, the logistics performance index for a developing country is something like 50% of that of a developed country... On their side, (Reda et al., 2020) studied the features of developed, emerging and developing countries in matter of city logistics. Based on an extensive literature analysis (more than 300 articles were studied), they demonstrated that the main logistics and supply chain issues for developing countries are city logistics problems. Notably, they remind the key features of these countries, already mentioned in (de Almeida-Guimarães et al., 2021), regarding the last-mile delivery question: very high traffic congestion and high level of unsafety on roads; high growth of population (i.e., consumers but also drivers); few and poor-quality infrastructures (roads, rails, ports/airports...); expensive, polluting and unreliable vehicles. They also identify those developing countries are working now on some hot topics such as crowd-shipping, urban consolidation centres, e-commerce delivery, loading/unloading areas, alternative transportation modes, and parcel lockers (Reda et al., 2020). But despite efforts and investments made by scholars and practitioners during the last decades to improve the city logistics activities of developing countries, the problem remains critical, both in terms of effectiveness and efficiency. Basically, these countries must cope with numerous structural problems such as low income per capita, dependence on specific sectors, low productivity, limited opportunities for employment, poor health and education, inequality and corruption... But they also have to manage a lot of specific city logistics issues proper to developing countries such as safety, congestion, no parking spaces, old and/or unsuitable vehicles and of course poor road infrastructures. Therefore, developing countries have a major problem to manage in their city logistics activities if they want to support sustainably their economy (Tahir Masood et al., 2011). This is particularly true for Southeast Asia countries, like Cambodia, whose economy is mainly concentrated around big cities submitted to huge growth of population. In such a context, the main problem statement of this research work can be formulated as followed:

How to enhance the developing countries' city logistics activities performance?

Considering this question, an obvious approach to change the situation would consist in investing a lot in new infrastructures (roads, canals, rails, airports, seaports, etc.) and transportation means. Although this is an absolute necessity for these countries, such a strategy needs time... a lot of time (probably decades) before bringing concrete results to the society. Consequently, a complementary approach should also be considered. It might consist in exploiting and using differently the existing assets and resources to avoid wastes and produce more added-value to city logistics activities. This research project follows this last path to improve concretely and within a reasonable timeframe the current performance of developing countries' city logistics activities. In regards of the elements developed in the previous sections, and because developing countries' main cities are designed differently from those of developed countries in terms of organization and means of transport (Reda et al., 2020), the current research project suggests to focus on the transportation of goods, in developing countries' city

context. Indeed, transportation in developing countries is still junior in terms of maturity level, leaving therefore multiple avenues for improvement. In addition, improving transport in such a context should obviously allow improving the performance of logistics deliveries but also mitigating traffic leads, implying a reduction in environmental and noise pollution, an increase in the level of health and the quality of life of the inhabitants (Jardas et al., 2016). Finally, the problem under study in this research work can be stated more precisely as followed:

How to improve the performance of freight transport activities in the cities of developing countries by using the existing means and infrastructures?

Concretely, the current research project wants to study a new way to manage transportation activities which is more relevant for these countries on one hand, and which is more able to benefit from new opportunities offered by the incoming society where developing countries are now living on the other hand. The research project will not try to simply transfer existing solutions from developed countries. It would have taken too long to cope with today's reality and challenge additionally to the loss of time and resources to reach such level. Consequently, the project will definitively ambition new and innovative solutions. Regarding this challenge, Physical Internet (PI) appears as a potential lever able to support the developing countries' city logistics transportation. The next Chapter will elaborate on this assumption in order to formulate a set of precise research questions and an associated research methodology.

CHAPTER II. RESEARCH ASSUMPTIONS, QUESTIONS AND METHODOLOGY

“The first step is to establish that something is possible; then probability will occur. When Henry Ford made cheap, reliable cars, people said, 'Nah, what's wrong with a horse?' That was a huge bet he made.”

~ *Elon Musk, CEO of Tesla, SpaceX and the Boring Company (February 6, 2018)*

As we have seen in the previous Chapter, developing countries have numerous challenges to manage in terms of supply chain and logistics networks such as safety, pollution, congestion, old and/or unsuitable vehicles, long lead times, economy, wastes and of course poor infrastructures. While developed countries have started to change their mindset and toolboxes for better managing their material flows all along their logistics networks, it is not really yet the case for developing countries. This research work intends to study potentials benefit for these countries if they consider drastic changes of the way physical of material flows are managed.

In such a context, we consider the recent Physical Internet (PI or π) paradigm as a potential solution for solving our problem statement, namely how to improve the performance of freight transport activities in the cities of developing countries by using the existing means and infrastructures.

In this Chapter, we introduce in details the PI as it is the backbone of our research developments. Then we present our research questions and the research methodology we developed for solving them.

1. Research Assumption: Physical Internet as a Potential Solution

The Physical Internet (PI) is a recent and innovative concept of interconnected logistics networks capitalizing on the ability to share resources and information (Montreuil, Meller, et al., 2012). In other words, the concept of PI refers to the integration and optimization of various physical transportation networks and infrastructure, including roads, railways, air and water networks, in order to create a more efficient and sustainable global logistics system. This concept has gained increasing attention in recent years as a potential solution to the challenges facing the traditional transportation and logistics industry, such as congestion, pollution, and the need for more resilient supply chains. This concept of PI was born in order to satisfy the increasing requirements in terms of environment and performance of services. Indeed, the current logistics system, particularly in developing countries, presents dysfunctions that are harmful to the environment and tend to compromise the sustainable development objectives (Ballot et al., 2014). Before it is too late, the PI was designed to offer a chance for logistics services to be more resilient, efficient, sustainable, and adaptable for its users by changing the way physical objects transit through the network (Montreuil, Meller, et al., 2012; Montreuil et al., 2013). In terms of stakes, most of the theoretical advantages of PI usage have been studied and demonstrated in various application domains (Sallez et al., 2016). But almost all instantiations of PI concern developed countries and not really the rest of the world. This remains to be explored.

1.1. Physical Internet Overview and Potential for Developing Countries

The original manifesto of PI consists in changing the manner in which physical items are managed, delivered, transported, stored, realized, supplied, and used to achieve global logistics efficiency and sustainability (Montreuil et al., 2013). The idea of the PI has been put up as the Digital Internet (DI) metaphor with 13 important qualities (Montreuil, 2011), such as encapsulation, openness, and universal interconnection, with the aim of enhancing the current global logistical systems. The PI is an open networked logistics that requires Internet connectivity and collaboration (Maslarić et al., 2016). The PI adopts the idea from the DI, which are open and interconnected networks, and aims to transport physical goods stored in standardized PI containers similar to the data transferred by packages in the digital world.

One of the key definitions of the PI indicates that PI is “a global logistics system built from the interconnection of logistics networks through a standardized set of collaboration protocols, modular containers, and intelligent interfaces for increased efficiency and sustainability” (Ballot et al., 2014). As highlighted in this definition, PI proposes a rethinking of the fundamentals of logistics. The term “interconnection” (or hyperconnectivity in other references) thus refers to the close and intensive connection between actors and network components. The second key aspect of PI is the desire to open up logistics networks and share assets. Today, companies form private and relatively stable networks that own their own warehouses and vehicles in general. PI breaks with this logic and assumes that assets should be shared among all users of this new network and used as needed. Moreover, PI as a "network of networks" seeks to increase visibility and the possibility of new connections between actors. The third key aspect of the PI is the use of intermodal transportation, which involves the transfer of cargo between different modes of transport without the need for intermediate handling. This can be achieved through the use of

standardized containers and other packaging solutions that can be easily transferred between ships, trains, trucks, and planes. The use of intermodal transportation allows for greater flexibility and efficiency in the movement of goods, as well as reduced handling and storage costs.

Another important aspect of the PI is the use of digital technologies to improve the efficiency and visibility of logistics operations. This includes the use of sensors and other IoT devices to track the location and condition of shipments, as well as the use of data analytics and machine learning to optimize routes and schedule deliveries. By leveraging these technologies, logistics companies can better predict and respond to demand, reduce waste and inefficiencies, and improve customer service. The PI also promotes the use of alternative modes of transport, such as electric and autonomous vehicles, in order to reduce the environmental impact of logistics operations. This includes the use of electric trucks, trains, and ships, as well as the development of “last mile” delivery solutions that use electric bikes and scooters to reduce emissions in urban areas. In addition, PI seeks to promote the use of sustainable fuels and energy sources, such as biofuels and renewable electricity, in order to further reduce the carbon footprint of logistics operations.

There are several challenges to the development and implementation of the PI, however. One major challenge is the need for greater coordination and collaboration between different transportation providers and logistics companies. This requires the development of new standards and protocols for intermodal transportation and the sharing of data and infrastructure. In addition, there are regulatory and legal barriers to the development of the physical internet, including differing safety and environmental regulations across different countries and regions. Basically, such a paradigm shift in logistics requires significant transformations at various levels. In other words, the accessibility challenge is consequent. It is necessary to get adapted information systems using advanced technologies to enable the hyperconnection of actors, allowing increased and standardized information sharing and massive data storage (Montreuil et al., 2010). Then, it will be necessary to make the actors accept to evolve towards this new mode of operation and to engage efforts in this direction. The expected investments will be mainly financial and time related (Grest et al., 2019). In this respect, the ALICE (Alliance for Logistics Innovation through Collaboration in Europe) grouping has recently published a roadmap formulating the important steps and associated prerequisites for the implementation of the PI by 2050 in developed countries (ALICE-ETP, 2020). However, we can notice that digitalization of developing countries is quite good, and the key players seem ready to explore innovative solutions instead of duplicating old ones issued from developed countries. As a consequence, it seems reasonable to consider the PI accessibility issues feasible in the context of developing countries. Actually, despite these challenges, the PI seems to have the potential to revolutionize developing countries in matter of transportation and logistics industry, by improving efficiency, sustainability, and resilience. Also, by optimizing the movement of goods and people across different modes of transport and leveraging digital technologies, the PI could create a more connected and efficient global supply chain, benefiting consumers, businesses, and the environment.

To sum up, the PI is slowly being implemented almost everywhere in the world, but it needs to be more widely known and especially convincing to be more widely adopted, especially in

developing countries. This project therefore aims to show whether or not PI is of interest to solve our problem statement, which is how to improve the performance of freight transport activities in the cities of developing countries by using the existing means and infrastructures.

1.2. State of the Art on the Physical Internet Concept

Recently, several studies have been published Systematic Literature Reviews (SLR) on the PI, such as (S. Chen et al., 2022; Matusiewicz, 2020; Sternberg & Norrman, 2017; Treiblmaier et al., 2016, 2020) as well as (Luo, Pan, et al., 2022; Luo, Wang, et al., 2022). These studies added to both theory and practice of PI and identified potential avenues for PI implementation. Essentially, the PI-oriented research works could be divided into five categories as shown on the following Figure 7: PI concepts, PI assessments, PI components, Innovative facilities used in the PI, collaboration in the PI (S. Chen et al., 2022). A sixth category related to the implementation could also be considered regarding to the practitioner perspective.

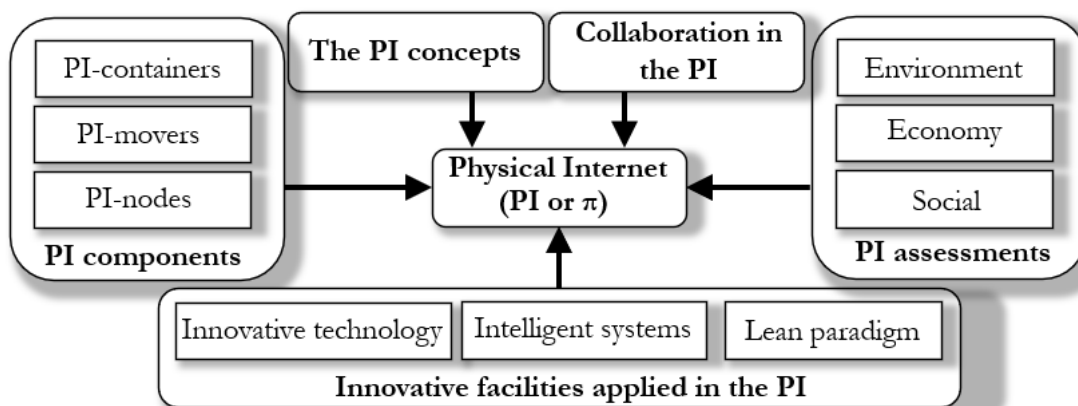


Figure 7: The existing research frameworks in the PI field (S. Chen et al., 2022).

1.2.1. The PI Concepts

The PI concepts are associated with the foundation of the development and performance of the PI. The PI concepts are created using the DI metaphor and are initially offered as one of the possible logistics solutions (Montreuil, 2011). To improve understanding of the PI in the current real-life context, the concept was modified as a four-layer network that supported an innovative business model for global logistics organizations. The first layer is the realization web (open production, personalization, and retrofit centres). The second is the distribution web (open distribution centres and warehouses). The third layer is an open multimodal mobility web that is composed of open unimodal and multimodal hubs and transits. The last layer, the physical-internet-enabled logistics web can infinitely (re)combine via these three-layered webs (Montreuil, Rougès, et al., 2012). Meanwhile, (Montreuil, Ballot, et al., 2012) developed another seven-layer open logistics interconnection (OLI) model for the global, open, and interconnected PI. According to (Matusiewicz, 2020), the PI is an innovative logistics network built on technology and collaboration that deserves the attention of both academics and practitioners. Recently, (Dong & Franklin, 2021) highlighted and addressed issues with a PI implementation based on an assessment of existing PI concepts. However, (Ballot et al., 2021) tried to identify specific PI concepts considering technological, business, and governance perspectives.

1.2.2. The Collaboration in the PI

The predominant characteristics of PI, such as openness and interconnectedness, make collaboration a must for PI implementation; nonetheless, a lack of collaboration is a critical barrier to PI realization (S. Chen et al., 2022). Many studies addressed the significance of collaboration in the PI and proposed practical strategies to improve multiple types of collaboration in the PI. For instance, a study by (Simmer et al., 2017) identified collaboration constraints in the PI and proved its crucial significance in the PI realization process. Recently, (Plasch et al., 2021) investigated and claimed motivational and success factors influencing business collaboration in the PI. Existing articles offered numerous strategies for improving organizational partnerships by addressing specific needs. Collaboration in supply chains through resource sharing is critical for the PI technique. A study by (Habibi et al., 2018) examined the collaboration issues of PI-hub locations and considered cost-sharing as a feasible solution for PI collaboration. To encourage collaboration in the freight transport network, an effective technique for building collaborative rules (Lafkihi et al., 2020) and a platform including a set of collaborative strategies (Vargas et al., 2020) were established. (Lafkihi et al., 2020) investigated and found two important aspects: network and market characteristics (e.g., demand-to-supply ratio) and carrier competition. In particular, information sharing is an essential component of collaborating in the PI. On their side, (Hofman et al., 2016) introduced semantic technology for enabled innovative supply chain and logistics networks as adaptive synchromodal planning by improving visibility and consequently predictability of turnaround times at container terminals. The study intended to address the notion of synchromodal transport and the PI. The information sharing in the PI is crucial. In terms of PI features, research into effective collaboration solutions is the first approach to organizations sharing assets (Lafkihi et al., 2020).

1.2.3. Assessments of the PI

Since the PI strives to enhance the existing unsustainable condition of logistics (Montreuil, 2011), reviews of the PI assessments have taken steps to examine its effectiveness from environmental, economic, and social perspectives, emphasizing the potential benefits given by the PI. Several studies (Kim et al., 2021; Treiblmaier et al., 2020) have shown that PI can greatly improve environmental and social performance. Of course, carbon emissions, such as greenhouse gas emissions, are one of the environmental challenges that logistics management must solve (Montreuil, 2011). According to several research articles (Fazili et al., 2017; Kim et al., 2021; Peng et al., 2020; Sarraj, Ballot, Pan, Hakimi, et al., 2014; Sarraj, Ballot, Pan, & Montreuil, 2014) emphasizing this issue, the PI can effectively minimize carbon emissions compared to other logistics networks by optimizing transportation means utilization. Correspondingly, (Fazili et al., 2017) studied the comparison of PI performance and conventional logistics system to measure the advantages and disadvantages of PI. The analysis shows that PI could reduce truck driving distances, times, cost and carbon emission. Instead, it increased the number of PI-container transfers within the PI logistics centers. In a recent study by (Kim et al., 2021), PI offers a conceptual framework to overcome urban last-mile delivery challenges such as growing customer demand, fast lead time, punctual delivery expectations, and urban environmental requirements. They introduced a system architecture of hyperconnected urban logistics in the simulation-based experiment to address the fragmented logistics operations, for instance, low efficiency and quality, seamless asset sharing, and flow

consolidation. The results could improve through economic efficiency, service capability, and sustainability. Economically, the PI can optimize the cost-effectiveness of the logistics network by shortening the driving distance and lead times (Fazili et al., 2017; Ji et al., 2019; Peng et al., 2020; Sarraj, Ballot, Pan, Hakimi, et al., 2014; Venkatadri et al., 2016). (Venkatadri et al., 2016) indicated that both the traditional logistics system and the PI have cost-cutting advantages, but the PI is better at diminishing total cost. In another research work, (Ben Mohamed et al., 2017) investigated the issue of urban transportation in a PI-enabled setting by applying multiple types of vehicles. They found that PI interconnectivity and extra hubs could improve urban transport planning regarding to routing efficiency and postponed services. With another perspective, (Y. Yang et al., 2015, 2017) introduced the mitigation of supply chain networks disruptions on hubs and factory plants and investigated the inventory model resilience through the PI framework of interconnected logistics services. They wanted to introduce PI disruption mitigation strategies by using simulation modelling technique when plants, warehouses, hubs and distribution centers became unserviceable for a period of time. The results of this technique helped to deal with disruptions in terms of penalty, transport and total costs. The PI also performs well in terms of leveraging social value. For example, the PI can strengthen drivers' working experiences (Fazili et al., 2017). Since PI is used to optimize the utilization of each container (e.g., π container) and truck and improve the routing systems, it gives alternatives for work-life balance (Z. Hu et al., 2019).

The majority of these studies on the PI were undertaken in Europe and focused on city logistics systems (Z. Hu et al., 2019).

1.2.4. Components of the PI

The PI usually focuses on three basic components: PI containers, PI movers, and PI nodes like PI hubs (S. Chen et al., 2022). The following will describe each of them.

π -containers: The least transport unit in the PI-enabled supply chain is modular and standardized PI containers (Landschützer et al., 2015; Qiu et al., 2015). The PI containers (π -containers) are critical components of the PI paradigm. One of the critical points to success in the PI implementation of logistics networks is a standardized container design. (Sternberg & Denzel, 2021) study identified two key aspects of this method: design methods and increased utilization (optimization usage) techniques for PI-containers. Indeed, the design concept for PI containers is crucial to the PI since the design architecture and attributes of PI containers impact container flows in the networks (Sternberg & Denzel, 2021). Considering the first key is the design methods of PI containers. The study (Landschützer et al., 2015) for instance examines the features and requirements of PI containers for the Fast-Moving Consumer Goods business. They proposed and discussed the design methodology for PI containers that took the perspectives of sizing, design, and loading into account. The second key is the utilization maximization of PI containers. (Y.-H. Lin et al., 2014) formulated a mathematical methodology with a non-linear objective function for selecting the optimal number of modular containers to pack a set of products to maximize space utilization. Increased space utilization at the unit load level was considered in this study. Similar mathematical model, (Deplano et al., 2021) set the priority parameter for PI containers (e.g., prioritized smaller bins) and added more constraints to make the problem and solution more realistic. The physical and informational flows of PI containers in logistics networks should be in synchronization and moving together, whether

partial loading, unloading, splitting, merging, etc. Therefore, the study (Tran-Dang et al., 2017) proposed wireless sensor networks (or wireless sensor nodes) developed for PI containers to efficiently track their movement.

π -movers: PI-movers are trucks, trains, cargo, and vehicles that transport PI containers' freight. Typically, PI movers focus on issues encountered during the transit process. So, (S. Chen et al., 2022) stated that the three main subjects for discussion are the scheduling problem, the routing problem, and the price problem in the matter of PI movers. Scheduling is related to decision-making, which could be classified as passive or initiative scheduling. (Wang et al., 2016) studied centralized and decentralized operation schedule modes for manufacturing. The centralized and decentralized operation modes are investigated using a hierarchical structure in passive scheduling and a flat structure in initiative scheduling, respectively. To embrace the PI, another study (Chargui et al., 2019) introduced truck scheduling solutions for truck transportation to address energy consumption (transferring PI containers from the train to outbound trucks) and cost reduction by using trucks for different destinations. The two meta-heuristics provided optimal solutions for the routing problem of transferring PI containers between cross-docking terminals. With collaborative routing protocols, PI containers can move through PI nodes (such as PI hubs) (Chargui et al., 2019). Correspondingly, a study of (Sallez et al., 2016) suggested a solution to the PI-container routing problem in cross docking hubs. They proposed an architecture of PI-container travel across the supply chain. (Puskás & Bohács, 2019) investigated how to model PI processes using the findings of a freight holding problem. Their studies examined the feasibility of reconfiguring platoons in the PI system by establishing virtual transfer points to optimize the freight problem. With the PI context, two works (Qiao et al., 2019, 2020) studied the dynamic pricing problem for carriers and developed a solution model to optimize carrier benefits. The study took into consideration the forecasting and uncertainty of transportation requests at the chosen destination to investigate the LTL (less than truckload) request pricing and selection problem.

π -nodes: PI-containers from various PI-movers are restructured and reorganized in PI-nodes to meet the new needs of PI-movers leaving. The concept of PI-nodes or PI-hubs is to translate fluctuating user demands and orders into precise delivery jobs and to reallocate PI-containers to satisfy the demands of different modes of transportation (S. Chen et al., 2022). PI-hub in the logistics networks is associated with the construct and design of an efficient PI-hub and PI-hub networks, for instance, scheduling and allocation problems at PI-hub, and a creative inventory control model. (Karakostas, 2019) investigated PI-hub networks built in a simulation model that behaved like Jackson queueing networks to analyze the characteristic performances (such as throughput and queue size) of all PI-hubs in entire hub networks. The PI-hub network is designed based on practical demands. (J. Zhang et al., 2020) introduced a method for formulating and solving dynamic stocking decision problems to optimize PI-hub efficacy. They found that the scheduling problem impacts PI-hub management since proper scheduling defines PI-hub efficiency. (Kong et al., 2016) presented scheduling methods for perishable items in PI-hubs. They mentioned that PI-hubs are also involved with the allocation problem. (Walha et al., 2016) proposed a method for resolving the PI-hub allocation problem. Their research attempted to improve PI-hub efficiency by optimizing the transfer process of each PI container in PI hubs and the number of trucks used. Inventory management remains a critical issue in PI-enabled logistics systems. Several studies (Pan et al., 2015; Y. Yang et al., 2015, 2017) developed models

for inventory management based on the interconnected PI vision and iteratively assessed them to optimize performance.

1.2.5. Innovative facilities applied in the PI

Big data analytics, blockchains, and other intelligent assets and facilities are frequently used to support the PI realization to address current issues or optimize metrics in the PI (S. Chen et al., 2022). According to a study by (Zhong et al., 2017), the use of big data analytics in the PI context of logistics networks could significantly increase data visibility and improve performance evaluation efficiency. (Kantasa-ard et al., 2021) proposed a demand forecasting model in PI using machine learning methods to deal with fluctuating agricultural product demand in Thailand. To enable collaborative shipping in PI, (Vanvuchelen et al., 2020) developed machine learning-based optimization algorithms for joint replenishment problems in the supply chain (such as inventory holding, back-orders, order and transport costs, etc.). Similarly, (Puskás et al., 2020) tried to apply the reinforcement-learning-based decision model based on PI's requirements to optimize vehicle exchange in platoon collaboration. Blockchain is thought to be an optimal platform for ensuring the PI's basic needs, including interconnection and openness. As a result, several studies (Betti et al., 2019; Meyer et al., 2019; Treiblmaier, 2019) initially proposed the conceptual framework and simulation model to investigate the opportunities of using and combining blockchain structures for improving hyperconnected logistics in PI implementation. Intelligent or smart systems could work interestingly with PI-enabled logistics by streamlining the process of handling information flows. These smart systems are purposely developed to help with PI implementation through their own ability to independently collect and interpret information, make decisions, and self-act and evolve (Pan, Zhong, et al., 2019). For instance, the cloud platform for real-time control and management was studied by (Kong et al., 2020). (Rodríguez Cornejo et al., 2020) introduced the relationship between lean paradigms and the PI to map the process from the supply chain to the customers. Regarding lean thinking from the philosophical discipline, they suggested a tool, "Value Stream Map," to facilitate the transformation from the current logistics systems to the PI, for instance, by improving storage, reducing waiting times, and identifying unnecessary transport and movements.

1.2.6. The PI implementation

Typically, PI has been applying strategies to cope with unsustainability and improve the efficiency of the logistics system. Inspired by the PI-modular containers, (Faugère & Montreuil, 2020) proposed flexible ways for the design of smart locker banks to optimize the efficiency of last-mile delivery performance in big cities. Additionally, (Ambra et al., 2021) suggested a method for increasing the efficiency of freight transport in last-mile delivery. The proposed method aims to confirm the effectiveness and sustainability of the PI approach by reducing the empty driving rate in logistics networks with the universal opening of the PI network.

With the interconnected features of PI, (Luo et al., 2021) developed a modeling and solution strategy based on a set of PI-enabled intelligent logistics facilities and illustrated its advantages over conventional operations for bulky goods delivery services. Their study tried to maximize the carrier's profit and provide a stable income. Some studies (Luo et al., 2021; Zhong et al., 2015) attempted to increase the visibility of information flows and ensure the information could

be accessed in real-time. For example, (K. Chen et al., 2018) developed a PI-enabled building information model to investigate systems for prefabricated construction projects. Another study (I.-C. Lin & Cheng, 2018) looked at implementing the PI platform to deal intelligently with tasks like sorting solar cells and improving operational management efficiency in the solar cell industry.

Although Europe is a rich field for PI implementation, other regions, such as Saudi Arabia and Africa, have acquired an interest in PI adoption (S. Chen et al., 2022). For instance, (Jaziri et al., 2020) presented the advantages of implementing the PI in Saudi Arabia and suggested an integrative approach for PI implementation. In addition, (Mayuto et al., 2019) examined PI implementation in Africa by analyzing the strengths and weaknesses of transportation and logistics systems in African countries.

Another viewpoint on PI components is that most existing research has focused on simplifying assumptions through computational experiments (Sarraj, Ballot, Pan, Hakimi, et al., 2014; Tran-Dang et al., 2017). In reality, real-life instances are frequently more dynamic, flexible, and complex.

2. Research Questions Formulation

As mentioned by (Tahir Masood et al., 2011), identifying and solving transportation problems is one of the key issues of developing countries. Despite efforts and investments that are made to improve the transportation means, the problem remains critical as we shown in Chapter I. Basically, these countries must cope with numerous transportation problems such as safety, pollution, congestion, old and/or unsuitable vehicles, long lead-times, wastes and of course poor infrastructures. This is particularly true for urban transportation as developing countries cities are growing very fast. In such a context, transportation must be more efficient and effective. Unfortunately, we must notice that it is not the case for now with critical consequences.

Given the circumstances, a clear solution to address this matter would involve making significant investments in new infrastructures such as roads, canals, rails, airports, and transportation means like vehicles, IT, and training programs. While this is an essential step for these countries, this approach requires a considerable amount of time, before yielding tangible benefits to the society. Consequently, a complementary approach should also be considered. It might consist in exploiting and using differently the existing transportation assets and resources and the new IT opportunities to avoid wastes and produce more added-value. This research project follows this last path to improve concretely and within a reasonable timeframe the current situation.

The ambition of the current research work is clear, though urban transportation in developing countries is still junior in terms of maturity level, we want to develop a new way to manage transportation activities which might be more relevant for these countries on one hand, and which might be more able to benefit from new opportunities offered by the incoming hyperconnected society where we live on the other hand. The project is not trying to simply transfer existing solutions from developed countries. It would have taken too long to cope with today's reality and challenge additionally to the loss of time and resources to reach such level. Consequently, the project is definitively developing new and innovative solutions.

The main idea of this research project is finally to demonstrate the potential benefits of managing transportation activities through an “interconnected” approach in developing countries. This project has the following concrete objectives for a developing country (non-exhaustive list):

- Reduce transportation lead-times
- Improve on-time delivery ratio
- Avoid useless travelled distance
- Limit waste of goods due to bad transportation
- Improve carriers' profitability
- Allow transportation multimodality
- Allow real time tracking of goods
- Optimize transportation costs

- Reduce carbon footprint impact of transportation

To reach the previous objectives, the current research project suggests to use the concepts and technologies of the Physical Internet (PI) initiative imagined few years ago. This work is based on the main assumption that the PI has a lot to offer to transform the urban logistics practices of developing countries. Consequently, the study will be concentrated on answering three main research questions (RQs):

RQ1 How can the principles of the PI be implemented in the context of city logistics in developing countries?

RQ2 How can the application of PI concepts to city logistics of developing countries be assessed in terms of its impact on performance?

RQ3 What are the concrete benefits that can be expected from the implementation of the PI on the case of city logistics in developing countries?

Basically, the first RQ intends to design a set of applicable scenarios that will be inspired by the PI paradigm on one hand, and that could fit with the key features of urban transportation and logistics of developing countries on the other hand. Our proposal on this subject will be developed in Chapter III as a conceptual contribution. The second RQ is about designing and implementing a dedicated experimental bench able to mimic the dynamic behavior of the previous scenarios in order to evaluate them quantitatively. This technical contribution will be presented in Chapter IV. The third QR deals with the issue of validation of the proposals made and the establishment of concrete recommendations. This business contribution will be developed through a field-oriented application case based on the city logistics activities of a Cambodian e-commerce company. It will be presented in Chapter IV too.

3. Research Methodology and Manuscript Organization

To answer these questions, we implemented a design science research methodology adapted from the information system research framework of Hevner et al. (Hevner et al., 2004), the methodological steps proposed by (Caillaud et al., 2015, 2016) and the methodological consolidation proposed by (Petitdemange, 2020). For these authors, the relevance of the research work conducted depends on the ability to meet and satisfy the business need. In our case, this work is relevant because the aim of this research is to provide concrete answers to the transport problems encountered by developing countries, especially in their cities. These problems are real and original as we have shown in Chapter I.

A study of the field is made in order to have a good understanding of the context, the stakes and the challenges to be taken up by the trade experts. This allows us to identify the particularities and characteristics of this domain compared to other sectors of activity.

A quantitative analysis of current performance is conducted in order to evaluate the concrete and objective issues of our research work. This phase allows us to qualify and quantify the extent of the industrial problems.

A bibliographical study completes the field study to identify the business (Chapter I) and scientific (Chapter II) issues dealt with in the studied field as well as the tools used to solve them. This study allows us to identify the gaps and to justify the tools and methods used.

The combination of the two previous studies allows us to formulate the scientific problem in the light of the gaps in the literature and the scientific obstacles in order to establish the problems that we wish to address and to present the hypotheses made (Chapter II).

The description of the models is detailed and argued and the modeling methods used are justified (Chapter III). This step also allows the verification of the replicability of the results.

Finally, based on the analysis of the experiments on the models produced in the previous step, a list of recommendations for the business experts is provided (Chapter IV).

Finally, to reach the goal of the current research, a nine-step methodology has been set up as a functional architecture, as shown in the Figure 8 hereafter. Inspired by the approach developed by (Vernadat, 2004) for supporting enterprise re-engineering and improvement processes, this methodology consists in four main phases which are: Conceptualize, Model, Experiment and Assess. These phases embedded the following steps:

- Step1: As our approach is field-oriented, this first step consists in selecting a concrete application case which is representative of the studied problem. In our context, the case should be a supply chain located in a developing country and having a high number of urban shipments to manage.
- Step 2: This step allows building a digital model of the current supply chain which includes the main features of the selected application case. This model would be able to simulate the AS-IS behaviors of the selected case.
- Step 3: This step consists in modelling the environment, and notably the urban characteristics, in which the select supply chain evolves. This model must be able to consider the specific developing countries' features (traffic congestion...).

- Step 4: At this stage, the two previous models are joint in a dynamic way to support simulations of the selected case behavior. Discrete event, multi-agent or systems dynamics models might be used to support this step.
- Step 5: This step consists in measuring objectively the performance of the selected supply chain in order to get a baseline. This baseline will be compared to other organizational alternatives, notably the ones which are based on PI.
- Step 6: From this step, the functional architecture moves to the definition, the modelling and the assessment of possible TO-BE organizations. Particularly, this step consists in designing a set of logistics scenarios likely to improve the overall last-mile delivery performance.
- Step 7: As for step 2, this step supports the modelling part of the potential scenarios previously defined.
- Step 8: As for step 4, this step consists in simulating the scenarios in the context of the environment defined and modelled in step 3.
- Step 9: Finally, this step allows measuring the performance of each scenario defined in step 6 and comparing their results with the baseline calculated in step 5 to make conclusions and deliver some recommendations to practitioners.

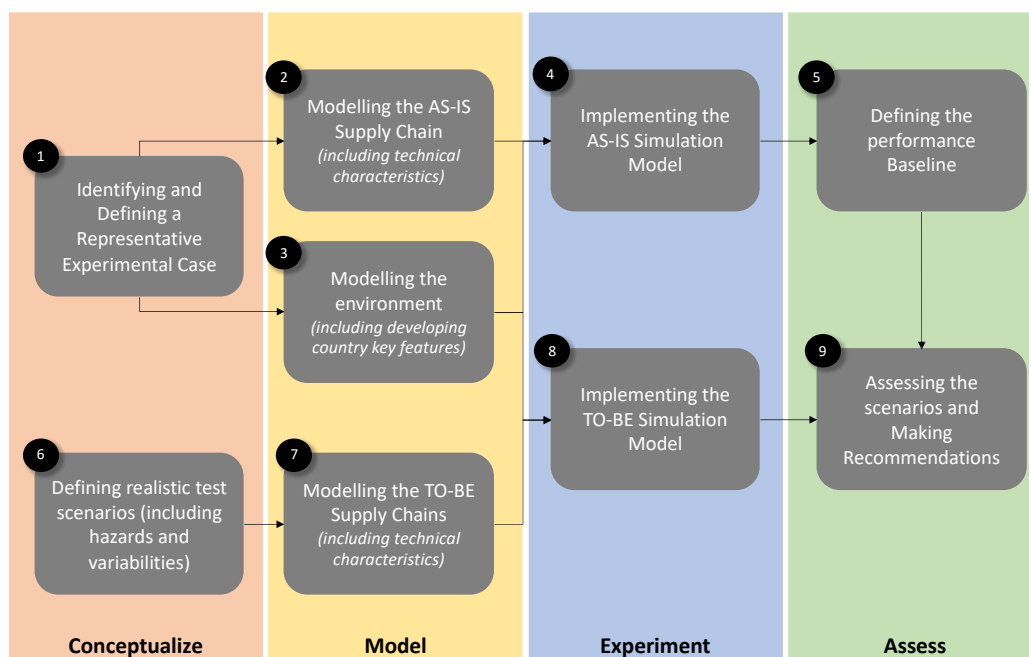


Figure 8: Research methodology.

This manuscript is organized in 5 chapters articulated according to the path described in the following Figure 9.

Chapter I focused on the description of the Problem Space related to the study. It reviewed the main characteristics of developing countries, particularly in Southeast Asia, and highlighted a number of logistics and transport issues specific to these countries that we propose to address.

Chapter II dealt with the Solutions Space that we propose to mobilize to address these business challenges, namely the use of the Physical Internet concept in such application contexts. In particular, it has allowed to bring out a set of research questions aiming at evaluating the interest

and the potential of using this paradigm in order to solve the main problem statement associated with this thesis.

The following Chapters (III and IV) will focus on the contributions as such. Chapter III will develop a set of organizational models, inspired by the Physical Internet, applicable to the case of urban transport management in developing countries. Chapter IV will describe the characteristics of the simulation model that has been developed to support the approach and will also discuss the main performance indicators used to analyze the results. Chapter IV will also focus on the implementation of an industrial experiment related to the case of goods transportation of an e-commerce company in the city of Phnom Penh in Cambodia. The results and associated recommendations will be discussed in this Chapter.

Finally, Chapter V will conclude the whole research work presented in this thesis and will open an important set of academic and business perspectives.

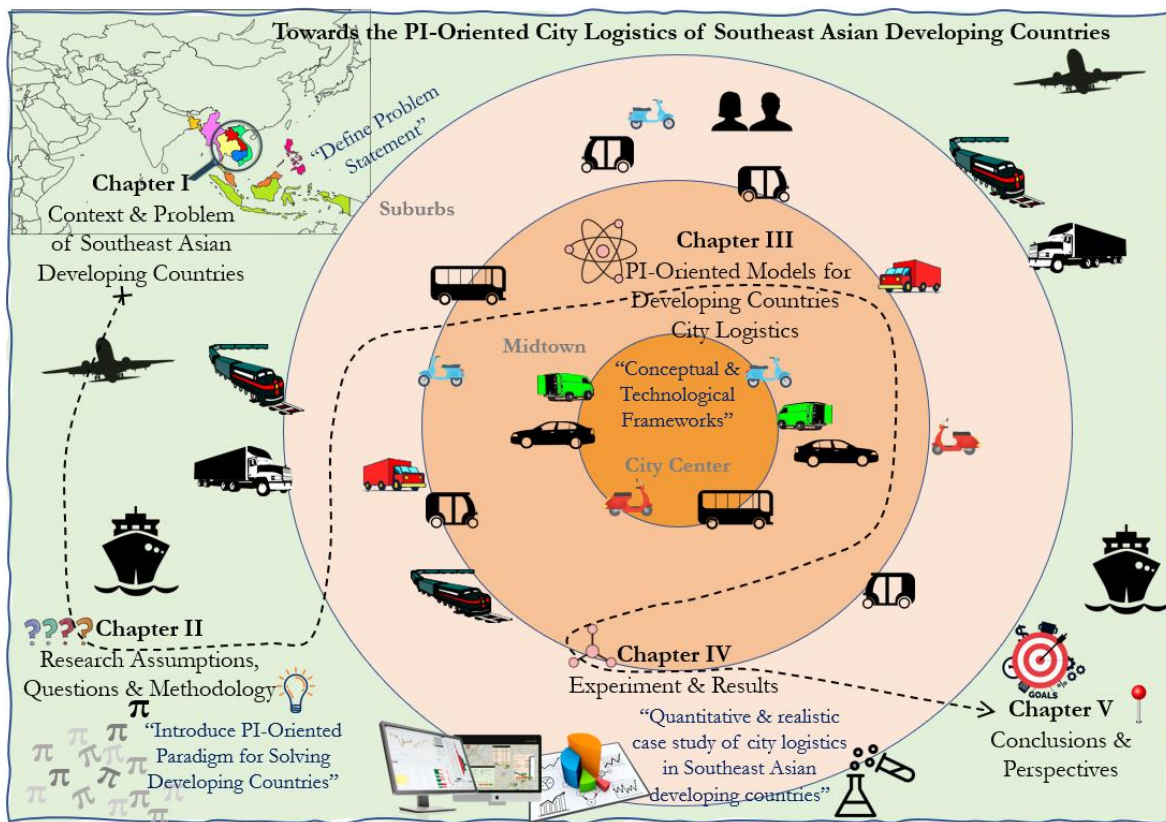


Figure 9: Manuscript Organization

CHAPTER III. PI-ORIENTED MODELS FOR DEVELOPING COUNTRIES CITY LOGISTICS

“Amateurs discuss tactics; professionals discuss logistics.”

~ *Napoléon Bonaparte (1769–1821)*

The previous chapters have helped define the context and pose the research questions. On this basis, we propose now to study the characteristics of what could be an urban logistics organization inspired by the Physical Internet (PI) paradigm. In particular, we will identify the most important potentialities for developing countries and propose related organizational schemes. A baseline model will also develop in order to support the assessment of the proposals.

Concretely, inspired by the study by (Crainic & Montreuil, 2016), the following aims to use nine key concepts for PI-oriented city logistics to improve urban logistics in developing countries. The goal is to create more efficient and sustainable city logistics systems. However, the study does not only aim to identify general concepts of PI-oriented city logistics but also to tailor and adapt these fundamental concepts for practical use in city logistics in developing countries.

Finally, this chapter presents a set of scenarios for PI-oriented city logistics systems, including features from developing countries as well as the key assumptions for each scenario.

1. Fundamental Concepts of PI-oriented City Logistics

The goal of PI-oriented city logistics is to diminish city congestion, emissions, and other negative impacts of traditional city logistics methods while also improving the reliability and responsiveness of delivery services in the city. This could be accomplished using a variety of means, such as real-time tracking and monitoring of vehicles and shipments, optimization of routes and schedules, and the use of alternative modes of transportation, such as electric vehicles. Furthermore, as demonstrated by (Crainic & Montreuil, 2016), some significant benefits of using PI paradigm in city logistics context can be expected such as reduced costs and environmental impacts, improved customer satisfaction, and increased competitiveness for businesses.

1.1. PI-oriented City Logistics Concepts

(Crainic & Montreuil, 2016) propose nine fundamental concepts for defining a PI-oriented city logistics system (also called hyperconnected city logistics) as described in the following Figure 10.



Figure 10: The nine fundamental concepts of PI-oriented City Logistics (from (Crainic & Montreuil, 2016)).

1-Worldwide intermodal network: Cities are interconnected nodes in a global logistics network that effectively moves goods using a variety of modes of transportation (intermodality). Cities are interconnected with each other and the larger logistics network, and logistics operations within a city are connected to global supply chain operations.

2-Information sharing and standardized systems: The use of data and information technology to enable real-time tracking and communication between different parties in the supply chain. In PI-oriented city logistics' systems, information sharing aims to improve visibility and transparency throughout the supply chain, optimize logistics operations, and reduce waste, for instance, shipping and delivery schedules, inventory levels, and the location and status of goods in transit. As a result, different stakeholders can have a clear understanding of the status and movements of goods within the city. So, it can improve coordination and collaboration between stakeholders and enable more efficient and sustainable logistics operations. Standardized systems are intended to ensure seamless integration and coordination with other cities and adopt standardized protocols, interfaces, and encapsulation methods.

3- Collaborative multifaceted activities: City logistics concerns a wide range of activities, including transportation, storage, handling, distribution, and value-added services, which are interconnected and interdependent. This concept involves connecting different modes of transportation, coordinating the movement of goods between different logistics centers, and integrating logistics operations with other urban systems such as transportation and communication networks. The partnerships and collaboration between different stakeholders, such as shippers, carriers, and logistics providers, can optimize the movement of goods within a city.

4- Distributed, multi-zone, multimodal architecture: Instead of relying on a single or a few logistics facilities, PI-oriented city logistics suggests to utilize a range of existing urban logistics facilities (e.g., public and private distribution centers, transport facilities, and parking spaces) and spaces in a distributed, web-like architecture that is flexible and adaptable to changing demand. The logistics hubs act as central connections between different parts of the city, using a network of transportation options and following both city policies and business strategies.

5- Open system stakeholder interconnections: The collaboration between a diverse set of actors, including logistics and transportation service providers, users, and authorities, to achieve consolidated and synchronized logistics operations. Open communication and transparency are significant for stakeholders to be able to see and understand the logistics operations of others to coordinate effectively. Multiple stakeholders could work together to create a smoothly functioning system through agreements, regulations, and policies.

6- Modular logistics containers: Using standardized, modular containers to package and transport goods can improve the efficiency and reliability of logistics operations within a city and beyond. PI-oriented city logistics uses standardized, smart, eco-friendly, modular containers of various sizes to facilitate the seamless flow of goods in and out of the city environment (e.g., enabling fast, cheap, safe, and reliable).

7- Integrated people mobility and freight logistics: The movement of people and goods within a city could be integrated and coordinated by using public transport vehicles, private service providers, and infrastructures for both purposes rather than separating them to optimize the overall transportation system.

8- Urban planning and logistics integration: Logistics operations should be integrated and considered in urban planning decisions in order to optimize the overall transportation system

and support the city's economic development. The urban layout and land-use policies have a significant impact on the performance of city logistics.

9- Sustainability, visibility, efficiency, and innovation: City logistics should consider the integration of environmental, social, and economic sustainability. The use of existing technology, such as the Internet of Things (IoT), apps, GPS, and other system tracking methods, has the potential to improve visibility and transparency throughout the supply chain. Optimization of resources and processes, such as π -containers, information sharing, open hubs and distributions, and stakeholder collaboration, can reduce waste and improve logistics operations' efficiency.

1.2. PI-oriented City Logistics Assessment

While this framework has been designed for developed countries, it seems to be applied to developing countries too. However, accessibility and stakes levels of each concept are different. In the following we suggest, for each dimension of the framework, to assess qualitatively (i) the potential impact on the developing country' city logistics performance and (ii) the accessibility of changing the current situation to reach such a PI-oriented city logistics ambition. This assessment is based on the developing countries features described in the previous Chapters:

1-Worldwide intermodal network: If developed countries' cities are mostly interconnected, this is not really the case for developing countries' ones, particularly at the worldwide scale. This concept could be considered as a major weakness for developing countries. Big cities are a few and most of the time their interconnection capabilities with worldwide supply chain network is very poor. Efforts to change the situation seem to be particularly not accessible as it implies major political and physical changes.

2-Information sharing and standardized systems: Despite a clear lack of infrastructures comparing to developed countries, most of the developing countries cities can today benefit from good telecommunication services (notably regarding 4G networks). As a consequence, most of the transportation means can be easily geolocated through some dedicated devices or more general mobile applications. However, this information is still poorly used in the context of the logistics activities. It can be said that there is a huge potential that remains to be used for better coordination and collaboration between stakeholders and thus for better performance of logistics operations. The standardized issues are probably much less advanced in developing countries as the used means are generally older and rarely fit with new rules and standards. Here again, the time to change the game should be very important as it depends of so many external factors.

3- Collaborative multifaceted activities: It is still common for companies producing goods and services in developing countries to manage their own warehousing, distribution and transport activities for end customers. This lack of business specialization often prevents companies from investing in the resources associated with logistics activities, which are often not considered to be part of their core business. This generally leads to logistics operations that are often far from the quality and cost standards known in developed countries. In addition, the number of logistics providers remains very small compared to the situation known in developed countries. As a result, urban logistics activities in developing countries suffer from a lack of

work decomposition between its different stakeholders, impacting quality and efficiency of logistics operations.

4- Distributed, multi-zone, multimodal architecture: This is probably the feature of PI-oriented city logistics defined by (Crainic & Montreuil, 2016) which is the most common in developing countries. Basically, city logistics activities of such countries are based on numerous urban logistics facilities, even rudimentary, particularly in matter of transportation. As there is no dedicated location and even, often, means for deliveries, the suggested flexibility of facilities recommended by (Crainic & Montreuil, 2016) is either something already existing or quite easy to get. However, this situation is more the consequence of a lack of structuring of logistics activities than the result of a genuine proactive policy. As a result, the system has many operational limitations and suffers from an inability to scale up.

5- Open system stakeholder interconnections: We are dealing here with a very rudimentary feature in the context of city logistics in developing countries. Indeed, as previously mentioned, logistics activities in these countries are still very much integrated with the companies that produce the goods. The question of interconnection therefore does not generally arise. However, this is a major issue and we can notice that in developing countries, various other sectors such as business or sales have a strong cultural capability of collaboration. Therefore, the perspective of changing this situation appears quite feasible.

6- Modular logistics containers: If the principle of using π -containers for city logistics activities is not dependent of its context, it must be noted that its implementation, beyond the maritime containers, remains something excessively rare; and this, whether in developing or developed countries. A considerable effort is therefore expected in this area in the coming years. Nevertheless, the possibility for developing countries to deploy this kind of solutions is greater than in developed countries because the growth is generally much more sustained and the existing assets to be decommissioned are much less.

7- Integrated people mobility and freight logistics: Mixing the movement of people and goods is quite common in developing countries' city logistics. Typically, vehicles such as tuk-tuk or public buses are used for both freight and passengers. One can consider this feature of PI-oriented city logistics as quite native in such a context.

8- Urban planning and logistics integration: Probably one of the most critical dimensions of the PI-oriented city logistics for developing countries. As far as for now, urban layout and land-use policies can be considered as chaotic and most of the time, mainly opportunistic. The huge growth of population and the high pressure that cities have regarding this point complexifies drastically their capability to design and apply coherent urban planning decisions.

9- Sustainability, visibility, efficiency, and innovation: Developing countries have to cope with two main difficulties regarding this objective of PI-oriented city logistics. First, the prevalence of existing technologies to support city logistics activities is low comparing to developed countries. As a consequence, it is particularly difficult to integrate environmental, social, and economic sustainability dimensions into them. Second, the poor performance of logistics activities recorded in developing countries imply a major focus on basic performance dimensions such as effectiveness or efficiency. Other performance dimensions such as

sustainability or innovation are not really considered for the moment and probably for some time.

Based on a rating scale from 1 to 4 and on previous developments, the following Table 1 and Figure 11 summarize through the principle of the Eisenhower matrix our assessment of accessibility and stakes of PI-oriented city logistics features for developing countries.

Table 1: Proposed qualitative assessment of hyperconnected features and challenges for developing countries ‘city logistics activities

| | Stakes | Accessibility |
|---|--------|---------------|
| 1-Worldwide intermodal network | 1 | 1 |
| 2-Information sharing and standardized systems | 3 | 4 |
| 3- Collaborative multifaceted activities | 4 | 3 |
| 4- Distributed, multi-zone, multimodal architecture | 1 | 3 |
| 5- Open system stakeholder interconnections | 4 | 4 |
| 6- Modular logistics containers | 3 | 2 |
| 7- Integrated people mobility and freight logistics | 1 | 4 |
| 8- Urban planning and logistics integration | 3 | 1 |
| 9- Sustainability, visibility, efficiency, and innovation | 2 | 1 |

1 to 4 Scale (1=low; 4=high)

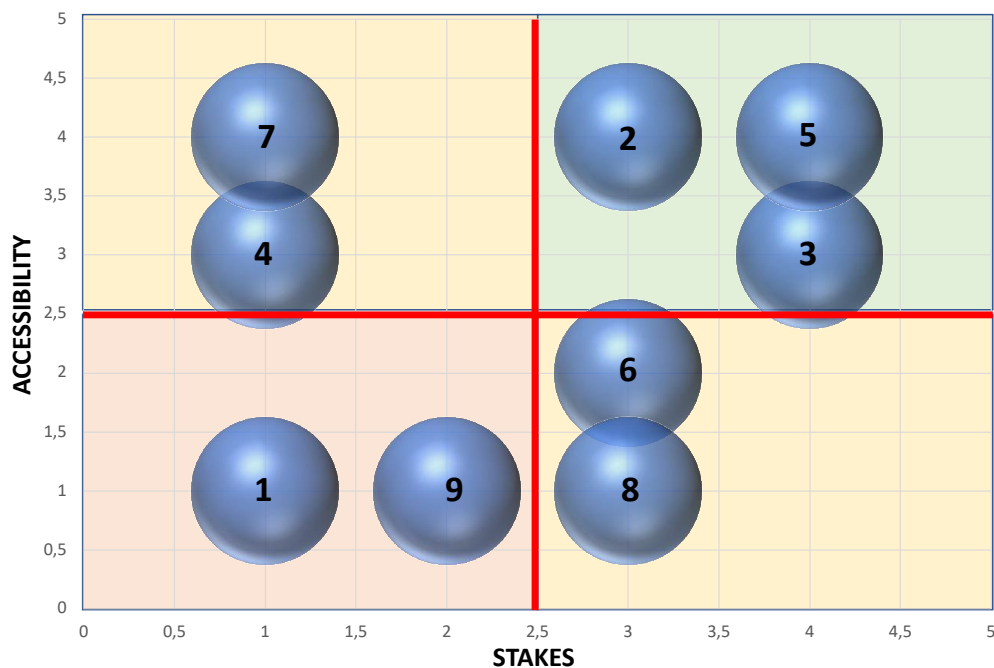


Figure 11: Prioritization matrix of hyperconnected features and challenges for developing countries ‘city logistics activities

It appears that the priority is on “Information sharing and standardized systems”, “Collaborative multifaceted activities” and “Open system stakeholder interconnections”. As a consequence, our proposal for modelling PI-oriented solutions for enhancing the developing countries’ city logistics activities performance will be mainly focused on those potentialities and objectives. Notably, the following proposals will be focused on how to better benefit from existing means and infrastructures for improving the performance of freight transportation activities. They will be based on the assumption that most of existing means and infrastructures are able to share

effectively information in a standardized way (see for instance geo-localization of transportation vehicles through GPS apps).

2. The Baseline Model

This section intends to define the baseline model that will be used as a reference for assessing the expected benefits of the PI-oriented solutions developed in the following. This baseline is directly inspired of the generic elements described in the previous chapters and of the background shared by the “Little Fashion Company”, a Cambodian e-commerce enterprise located in Phnom Penh City. Actually, we developed a long-term collaboration with this company all along the research work process in order to systematically close the loop with the field. More information about this specific use case will be developed in the next Chapter, in connection with the experiment of this research work.

This scenario (Scenario #0) is summarized on the next Figure 12. It considers a company composed of a single distribution center, called Main, able to store and prepare all the customer orders for the concerned territory (represented by the framing on the Figure 12). The company receives orders as they come in (24/7) and prepares and ships them on a FIFO basis, during the distribution center's opening hours (8am - 8pm). In this study, we consider that the distribution center has an infinite capacity of stock and that the order preparation times are constant. Only a variability related to the availability of transport vehicles is considered.

As far as transportation is concerned, we consider that this company has its own fleet of vehicles (essentially motorcycles in our case) capable of ensuring deliveries throughout the day according to a capacity depending on the type of vehicle used (motorcycle, van, tuk-tuk, etc.) and a pre-established schedule. The principle of the vehicle rounds is relatively classical, and is based on shortest path algorithms (Cormen et al., 2009; Dijkstra, 1959). The speed of the vehicles takes into account their intrinsic characteristics but especially the traffic characteristics of the territory concerned. In particular, congestion issues are systematically integrated into the model.

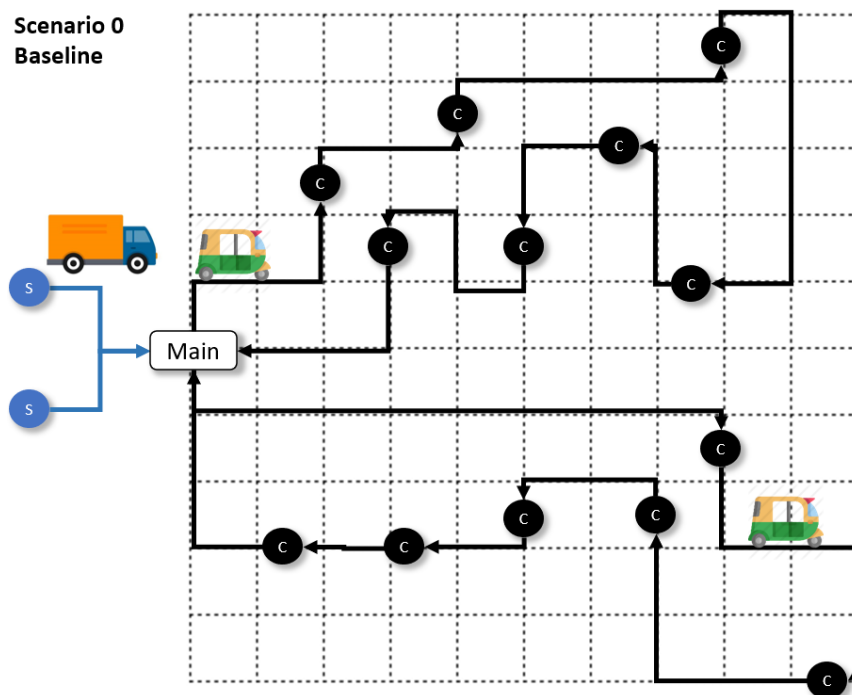


Figure 12: AS-IS Supply Chain scenario

The order fulfillment process considered in this scenario is described in the next Figure 13.

There is only one company (Main or the Main Hub), which operates a last-mile delivery service. Last-mile round is ensured by van or three-wheel motorcycle or tuk-tuks, because the rounds are quite long, and there is a need for capacity. In this case, the carriers would dispatch products to several customers. The delivery men travel from one customer to another customer location to deliver the products until they finish the delivery task, and then they return to Main and waiting for other new task. This efficient and effective process ensures that customers receive their orders in a timely and convenient manner, while Main is able to manage its fleet of carriers and optimize their utilization (See Figure 12 above).

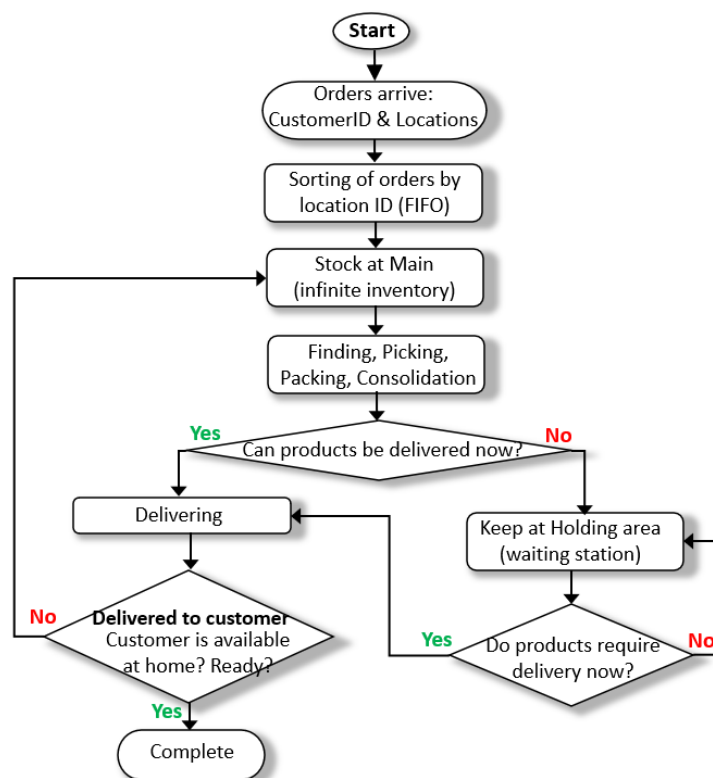


Figure 13: Baseline model of the order fulfillment process.

As shown in Figure 13 flowchart, the order fulfillment process starts with the arrival of orders that contain detailed information such as customer ID, latitude and longitude, start time and date, etc. These orders are then sorted by location at the main warehouse using the FIFO method. This ensures that all orders are processed in the same order they are received without any delay or priority given to any specific order.

Once the orders are sorted, the fulfillment team at the main warehouse starts the picking, packing, and consolidation processes. After the packages are ready, the exact time and date for delivery needs to be confirmed, which depend on the availability and appointment of the customers at home. If the packages are ready to be delivered, the process flow moves to the step of delivery, where the delivery team takes responsibility for the delivery tasks.

The next step in the process is to check if the customer is available at home. If the customer is at home, the orders are finally delivered to the respective customers, and the process is complete. However, if the customer is not at home, the package is not delivered and it will return to the Main Hub.

If the packages are not required to be delivered immediately but need to be delivered at a later date (usually within 1 or 2 days), the packages will be kept in the holding area (temporary storage area) until the delivery date. This ensures that the delivery process is streamlined and customers receive their packages on time.

3. The Proposed PI-Oriented Models

3.1. PI elementary components

As discussed in the previous Chapter, PI is enabled by three main elements: containers, nodes, and movers (see. Figure 14 below). π -containers are standardized containers that can be managed, moved, handled and stored by various companies. π -movers are used to move and manipulate π -containers such as π -vehicles (π -trucks, π -three-wheelers, π -tuk-tuks, and etc.). π -nodes are locations for receiving, storing, exchange, and transferring π -containers through π -movers. π -nodes can be π -hubs or π -cross-docks, π -transits, π -switches, π -sorter, π -composer, etc. The π -hubs are proposed to facilitate and enable the transfer of packages from incoming to outgoing π -movers. The goal is to deal with the packages directly rather than just the carriers. π -hubs enable unimodal packages cross-docking operations. π -hubs will be critical for efficient and dependable multimodal transportation because they enable the easy transfer of packages between suburbs, midtown, and the city center using a variety of modes of transportation, such as trucks, vans, three-wheel motorcycles, and motorbikes. This can be more efficient and cost-effective than relying on a single mode of transportation, as it allows shippers to choose the most appropriate mode for each leg of the journey. In general, π -hubs move or reposition packages from incoming transportation (π -movers) to a location within the hub where they can be loaded onto outbound transportation (π -movers: either the same mode of transportation or changing modes of transportation depending on the size of the packages and the traffic condition of the city). Meanwhile, these inbound π -movers that are coming into the π -hub are being filled with other packages and are leaving the π -hub. There is a constant flow of packages coming in, being moved, and going out of the π -hub.

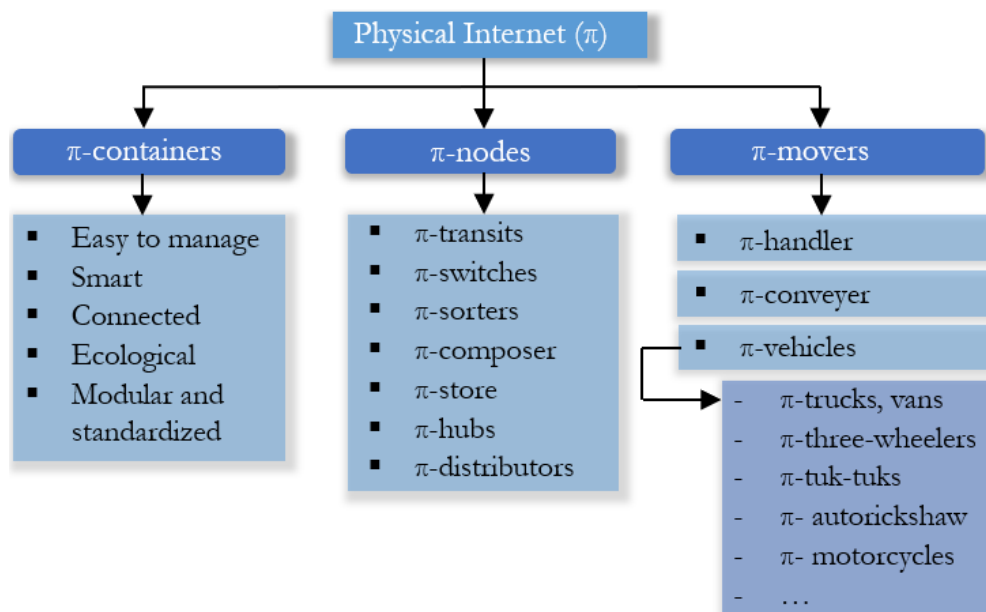


Figure 14: Crucial types of physical elements of the PI introduced in developing countries in general.

Finally, π -movers transport π -containers between some π -nodes (oftentimes π -cross-docks or π -hubs). In the context of our research, and accordingly to the prioritization matrix discussed earlier, we will make the emphasis on how the introduction of π -nodes and π -movers logic can bring value to the transportation in developing countries city logistics' activities.

3.2. Introducing PI Hubs

The following scenario proposes to add π -hubs to support the delivery of goods in the concerned city (see. Figure 15 below). Basically, the city is divided into several zones that are equivalent in terms of potential demand density. Each π -hub has its own fleet of vehicles (mainly motorcycles) to ensure last-mile delivery. It is responsible for the preparation, shipment and delivery of customer orders in its territory. The restocking between the (main) distribution center and the π -hubs is ensured by daily shuttles (mainly trucks or vans). The main stock remains at the distribution center and remains at infinite capacity. Note that some delivery points can possibly be handled by several hubs according to simple route consolidation rules. The tour organization algorithms are the same as those proposed in scenario #0. Nothing is changed regarding the supply, the customers' and traffic behaviors which must fit with the developing countries' features.

A possible direct extension of the scenario consists in adding the possibility to make transfer between the π -hubs.

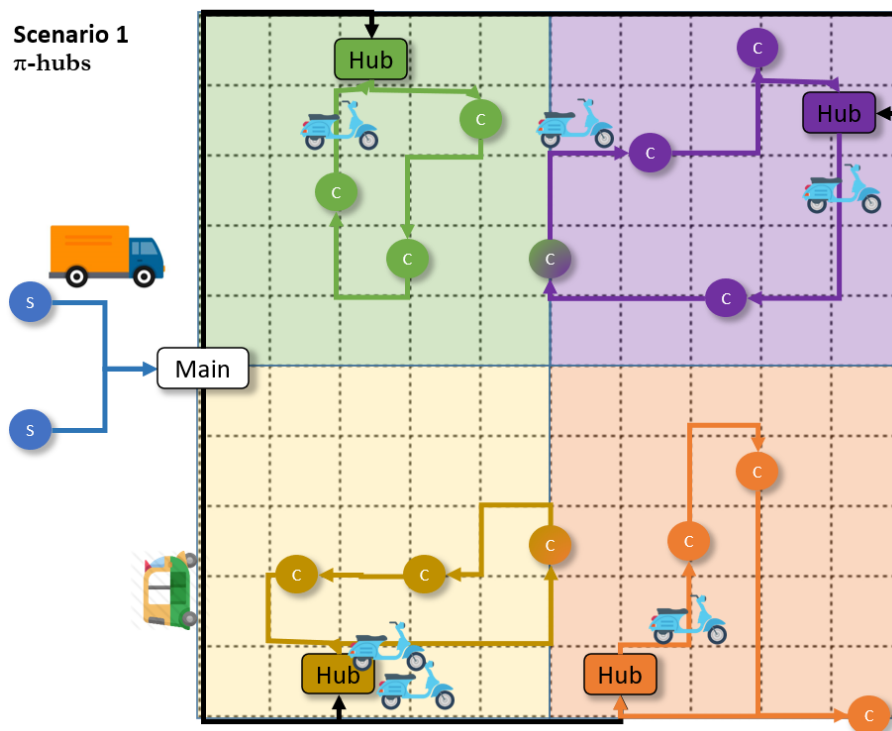


Figure 15: PI-oriented scenario #1, introducing PI hubs

In this scenario, the π -hubs behave as simple cross-docking platforms. The incoming goods are brought to the π -hub and then transferred directly to the outgoing transportation vehicles (motorbikes), without being stored at the π -hub (no inventory). This allows the goods to be shipped to their final destination more quickly and efficiently. The π -hub in this case is a location where π -cross-docking takes place. The main process flows of the order fulfillment is shown in Figure. 16.

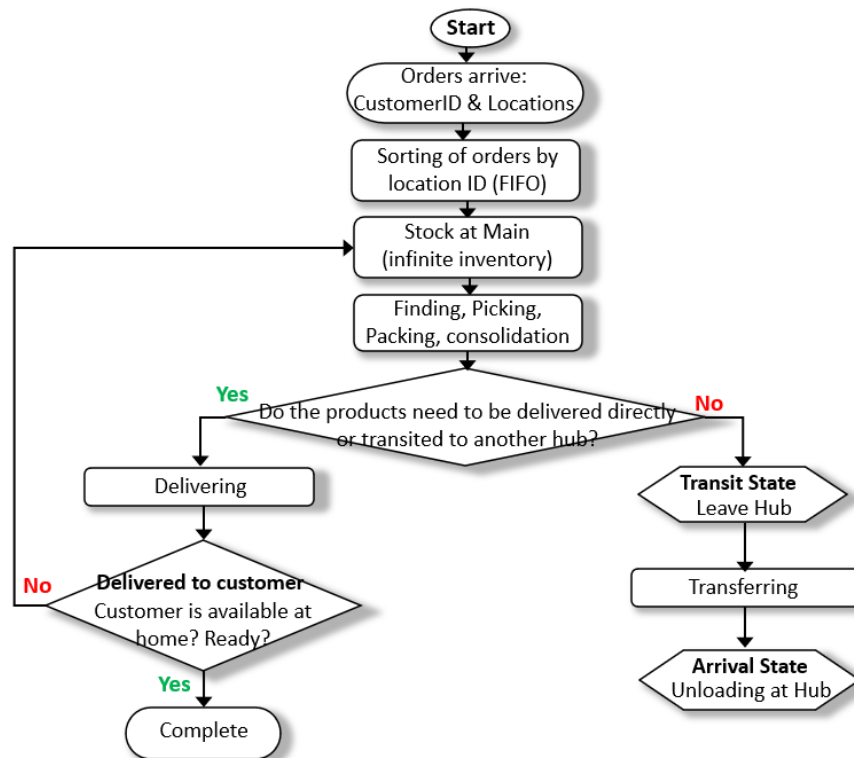


Figure 16: Main process flows of the order fulfillment process.

Figure 16 presents the process flows of customer order fulfilments at the Main Hub. The process flow chart of Scenario #1 is similar to Scenario #0, with the addition of Local Hubs as cross docking points between the Main Hub and customers. In this scenario, packages may need to transit through a Local Hub before they can be delivered to customers.

The process begins with orders arriving, which includes customer ID and location information and etc. The orders need to be sorted by location before they can be processed at the Main Hub. The Main Hub then processes these order fulfilments by finding, picking, packing, and consolidation the products by the fulfilment team at the Main.

Once the packages are ready to deliver, the system checks whether they need to be delivered now or if they need to transit through Local Hubs before reaching the customers. If the packages need to be delivered directly, the system follows the "Delivering" state, which involves physically transporting the product to the customer's location. "Delivery" means that packages are delivered to customers who are located surrounds Main Hub even though the packages need to transit hubs. In that case, "Delivering" state includes activities such as loading the product onto a vehicle, transporting it to the customer's location, and unloading it. However, before the delivery can be completed successfully, the system checks the availability of customers at home. If the customers are not at home, the package is returned to the Main Hub, and the delivery task is rescheduled.

Another critical flow in this Scenario, if the packages need to transit through Local Hubs, there are three statuses used to track their progress (e.g., barcode): "Arrive," "Transit," and "Delivered." The "Arrival State" status is assigned when packages enter a hub (e.g., scanned in). Soon or later, the packages may have to leave the hub, either to transit to another hub or to be delivered directly to the consumer's location at that point. This case, "Transit State" is used

when package leave hub to another hub (e.g., scan out). The material flows from hub to hub will keep the status of "Arrival State" and "Transit State" until they reach the nearest hub to the consumer's location. Finally, the status changes to "Delivered" (e.g., scanned out), indicating that the packages can be delivered to the customer. However, to complete the delivery task successfully, the customer must be available at home at the right time of delivery. If not, the packages will be returned to the hub and the delivery task will be rescheduled based on the availability of customers.

In a π -hub operation (the process flow is described in the following Figure 17), goods typically come from main warehouses or suppliers and are then received at π -hub (transit π -hub). The products are unloaded from the incoming vehicles (trucks, vans or tuk-tuks) and sorted and consolidated according to their destination. Without delay, the sorted products are loaded onto the appropriate outgoing vehicles, which are motorcycles in this case. Motorcycles finally transport the products to their final destination, such as a customer's location.

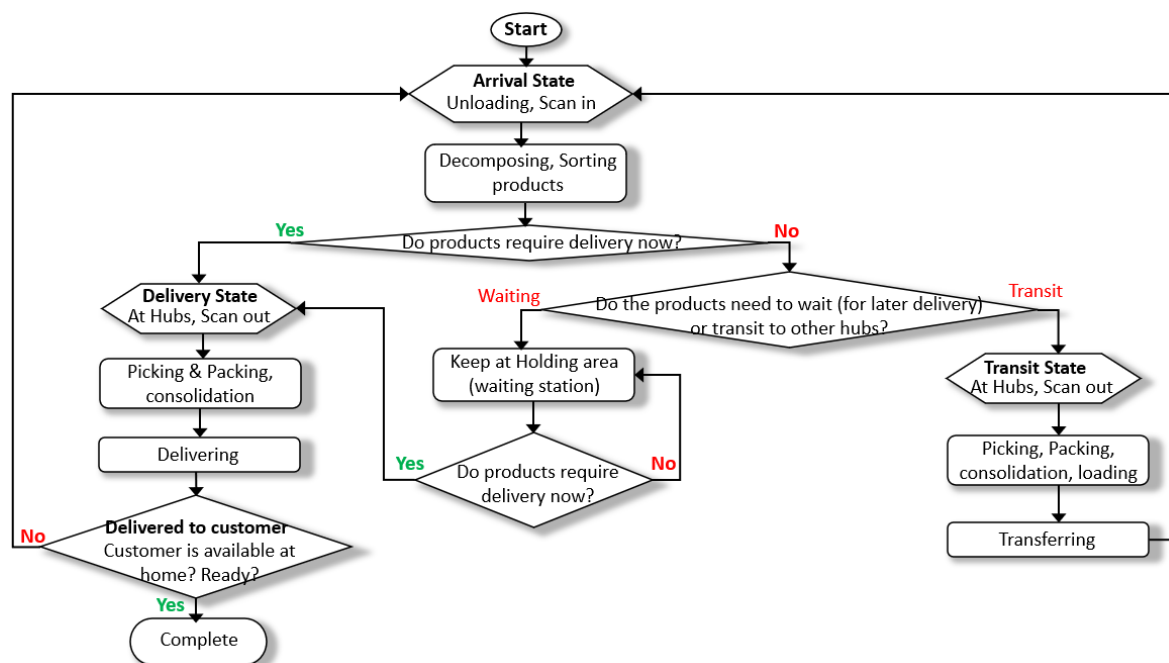


Figure 17: Hub process flows for introducing π -hubs in the network.

The process flowchart of Local Hub is shown in Figure 17. With PI principle, this is information sharing, the hub process flow is based on customer order fulfilments. When packages/items enter hub (the status is "Arrival State" e.g., scan in), these packages may need to unloading, decomposing, sorting by fulfilment team at hub. After that, packages must need to know about the delivery at the scheduled time either delivery now or later. If now, the flow will go to "Delivery State" (e.g., scan out to customers). That means packages leave hub and can deliver to customers. This task will be handled by outgoing vehicles who is hub delivery team. This case, the delivery team is available at hub to process order fulfilments. However, if customer is available at home or at the right place and at the right time, the delivery is complete. Otherwise, the package needs to return to hub which is "Arrival State".

Another flow at hub processes, if the packages are not delivered now, they need to check and ensure that the packages are waiting for later delivery (depending on the availability of customers) or transit to another hubs. If packages are waiting for later delivery, these packages need to keep at holding area until they can deliver to customer. Since the Local Hub plays a role as cross-docking, packages come in and must go out and they are not waiting too long. Also, hub does not have inventory in this case. If packages need to transit to another hub, they will follow to the “Transit State”. Similarly, packages may need to go through picking, packing and consolidation by fulfilment team at hub. After that they will be loaded to outgoing vehicles who are delivery team. Packages need to transit hub until they can reach the customer locations. If packages can reach customer location, the flow will go to “Delivery State” which mean they are ready to deliver to customer. If not, they are still “Arrival State” which mean packages still transit hub and they are not ready to deliver to customer.

3.3. Considering On-Demand PI Movers

In this scenario, the proposal is to get closer to the idea advocated by the PI about creating a shared, modular, standard, and interoperable transportation network that connects independent transport networks, like the Digital Internet (Montreuil, 2011; Montreuil et al., 2010; Pan, Trentesaux, et al., 2019). The use of modular components and standardized materials (physical, informational, and managerial) is essential for the success of a network because they help ensure that the network can easily connect and work with other networks seamlessly (Montreuil, 2011; Montreuil et al., 2010; Pan, Trentesaux, et al., 2019).

In order to think about a reasonable solution in terms of accessibility, and in coherence with the priority points identified previously, we propose here (Scenario #2) to entrust the transport of goods to third party resources. But not a dedicated, predefined third party. The proposal here consists in making the best use of the very numerous means of transport already available in a city of a developing country. As already discussed, these means of transport are very often capable of handling goods in addition to passengers. Thus, instead of attaching to each hub its own fleet of vehicles, the process imagined here will solicit available transport in the vicinity on the fly (tuk-tuks, motorcycle cabs, etc.). Finally, in this option, the chartering of transport becomes an "on-demand" activity depending of both the customer expectations and of the transportation opportunities around the π -hub.

The following Figure 18 describes this scenario (Scenario #2).

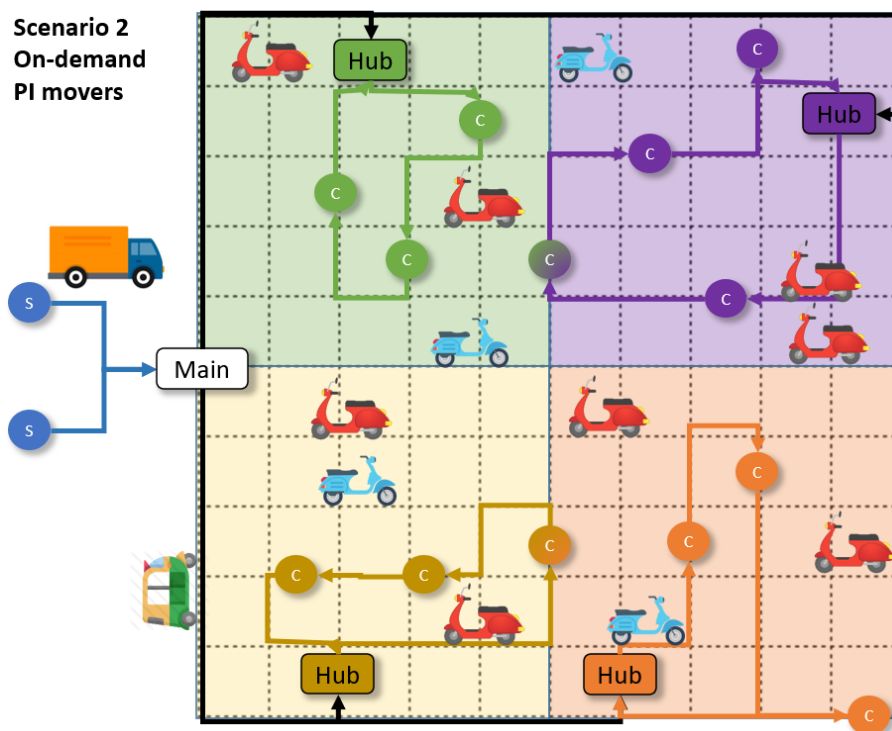


Figure 18: PI-oriented scenario #2, considering on-demand PI movers

In matter of process, this scenario runs as following (see next Figure 19): π -hub can use on-demand vehicles available in the city to transport goods to their destination. In this case, the steps for using on-demand vehicles would depend on the specific provider and services being

used. π -hub receives incoming goods from main warehouse and sorts them according to their destination. With the PI Network and information sharing, the on-demand vehicle provider can arrange for the pickup of the sorted goods from π -hub and deliver it to the customer's location.

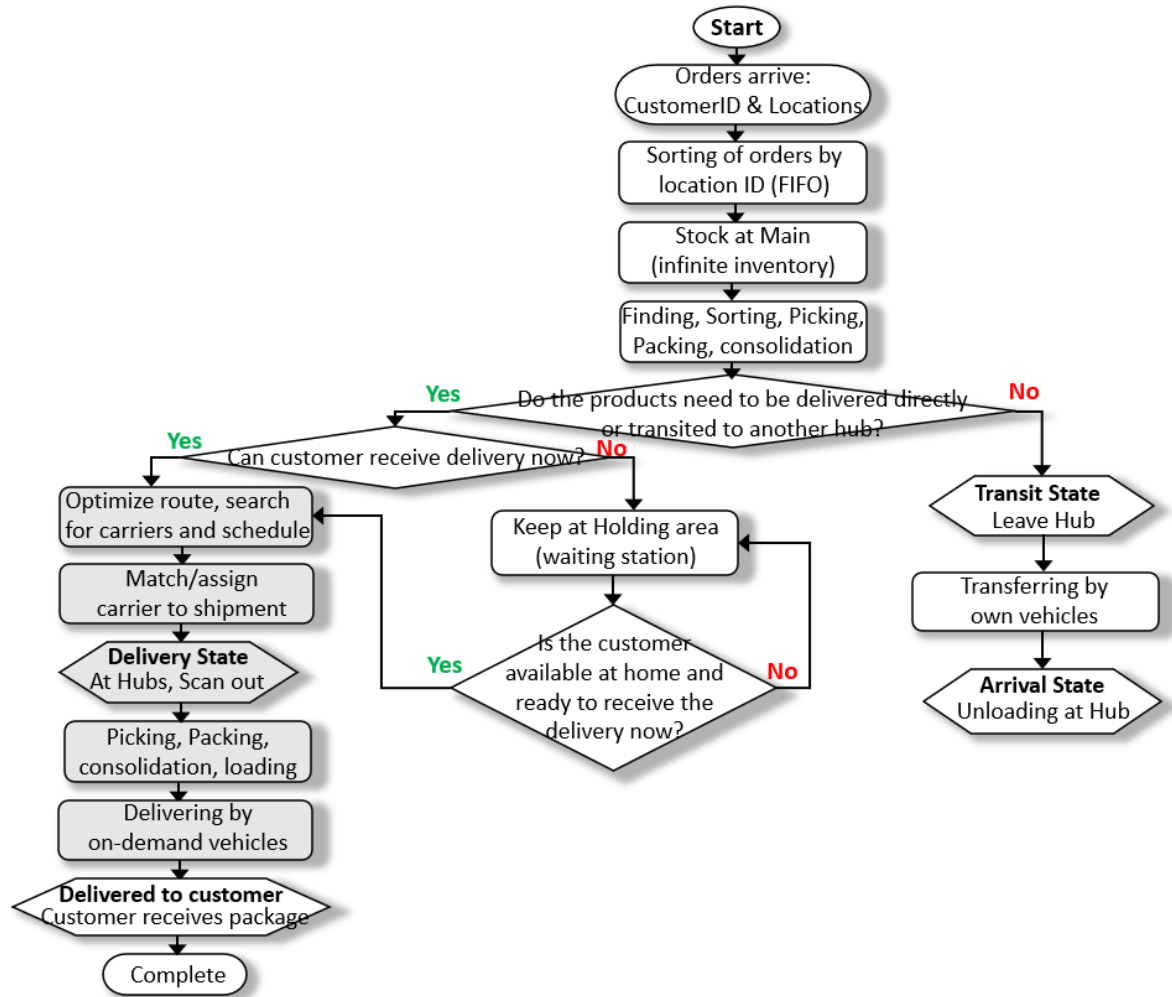


Figure 19: Main process flowchart of customer order fulfillments, considering on-demand PI movers

On the Figure 19 above, the PI collaboration scheme introduces open PI-hubs to facilitate the exchange of multiple carriers for last mile delivery. This enables different carriers to deliver products to customers efficiently. The process flow starts with customers placing their orders, which are received by the Main hub responsible for preparing the shipment for delivery. The Main hub has an infinite inventory.

After the packages are prepared, they need to be delivered to their destination either directly to the customer or to a transit hub. In this scenario, we introduce the PI-mover as an on-demand vehicle. The packages are logged into the tracking system with details such as weight, dimensions, and destination. This allows the Main hub to keep track of the shipment and provide updates to the customer about its status, such as when it has been shipped and when it is expected to arrive at its destination.

If the package needs to be delivered directly to the customer, the flow checks if the customer is available to receive the delivery. If so, an optimization algorithm is used to determine the most efficient route and search for available and capable carriers with delivery schedules. The Main

hub assigns a carrier to the shipment, and the carrier picks up the shipment and transports it. Finally, the shipment is delivered to the customer, and the delivery process is completed.

If the customer is not available at the scheduled time of delivery, the package is held in a storage area until the scheduled delivery time. Another flow, if the package needs to be delivered to a transit hub first, it goes to the “Arrival State” and may need to transit from hub to hub until it can be delivered (reach their destination delivery). When the package is ready to deliver, the flow checks the scheduled delivery time and customer availability to receive the products. If the customer is available, on-demand vehicles are used to deliver the packages.

It is important to note that packages in transit from hub to hub are carried by a delivery team employed by the Main Hub.

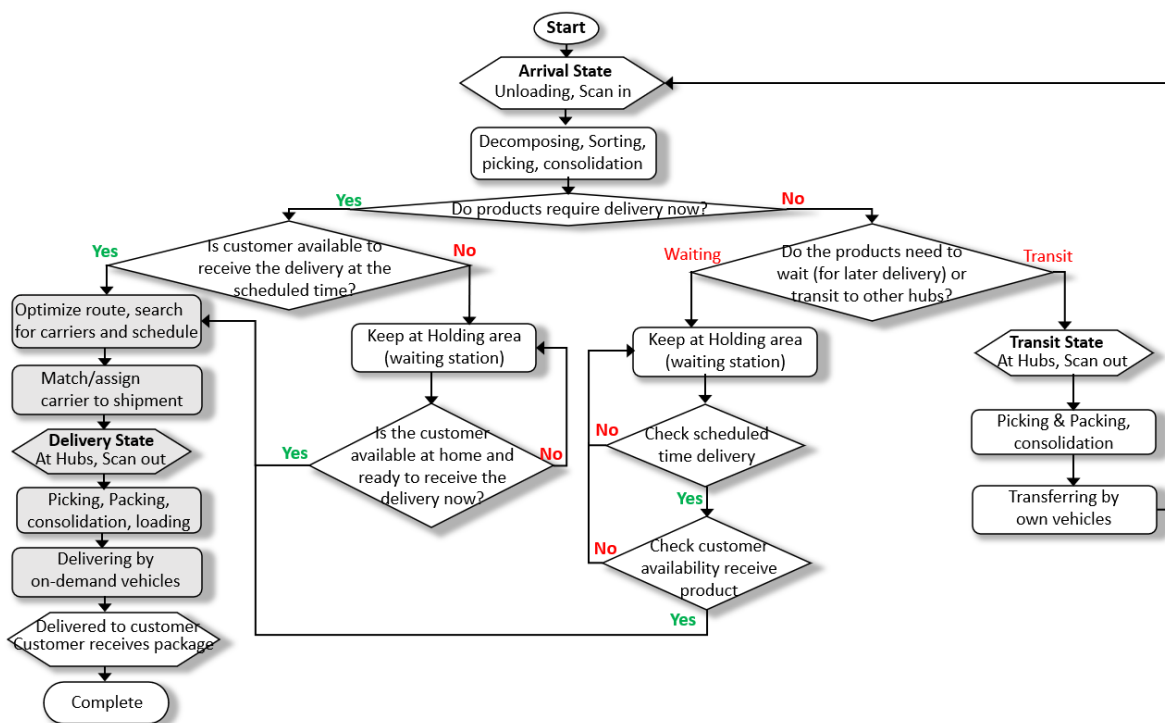


Figure 20: Hub process flowchart of order fulfillments, considering on-demand PI movers

The Figure 20 above shows the process flowchart of order fulfillments for this scenario. The process flow for open PI-hub here is similar to the previous scenario, but the difference is the involvement of on-demand vehicles. Shipments are delivered to an open PI-hub where multiple carriers are available for last-mile delivery. The shipment arrives at the open PI-hub in the Arrival State, where packages are decomposed, sorted, and consolidated based on their destination and other factors such as size and weight. At this point, packages can enter/log their detailed information into the tracking system. Logging the shipment into the system enables the open PI-hub to track the shipment throughout the entire delivery process, from the time it is picked up until it is delivered to the customer.

After that, the package status needs to be checked whether it requires delivery now or later delivery/transit to other hubs. If it needs delivery now, the flow checks the customer's availability to receive the delivery at the scheduled time. If the customer confirms okay, the process follows on-demand carriers. In this case, an optimization algorithm is used to determine

the most efficient route, and available and capable carriers and delivery schedules are searched. Then, the system matches or assigns a carrier to the shipment. Finally, the carrier comes to pick up the shipment and transport it to the customer to complete the process. If the customer is not available at the scheduled delivery time, packages have to wait at the holding area until they can be delivered.

Another state is either later delivery or transit to other hubs. Since packages arrived early, they have to be kept at the holding area for later delivery and wait for the delivery scheduled time. When the time to deliver comes, they have to check the customer's availability to receive the product. If the customer is available, the flow uses on-demand carriers to deal with the delivery. If not, packages have to wait in the holding area. In the transit hub state, packages need to transit from hub to hub until they can reach the nearest hub to the customers. At that point, packages can be delivered to customers in the Delivery State and scanned out. However, to complete the process of delivering the customer's product, the flow still needs to check the scheduled delivery time and the customer's availability to receive the packages. If everything is alright at this stage, packages can flow to the customer by using on-demand vehicles. In this scenario, real-time information sharing and collaboration among all stakeholders are crucial.

3.4. Toward a PI Network

For the moment, the proposals made were more about Physical Intranet approaches rather than Physical Internet since there was only one company. One ambition of the research work is therefore to consider the potential underlying resource sharing between several shippers. The scenario proposed here (Scenario #3) thus aims to consider two distinct companies that offer their respective goods to customers present on the same geographical territory. Although these companies are on different businesses, have different products and different customers, they share facilities and process regarding the last-mile delivery. Each of these firms has a distribution center (Main) capable of supplying π -hubs shared by both firms, based on the rules already defined in Scenario #1 and Scenario #2. In this scenario, last-mile delivery transportation is still managed according to the modalities proposed in Scenario #2, with the difference that the last-mile delivery rounds can be pooled between the orders from the two companies. Therefore, additional positive impacts can be expected (See Figure 21).

As with previous scenarios, this proposal includes consideration of the characteristics inherent in urban environments in developing countries: availability of transport, traffic patterns, hazards, etc. This is a mandatory condition to support the resolution of our research questions.

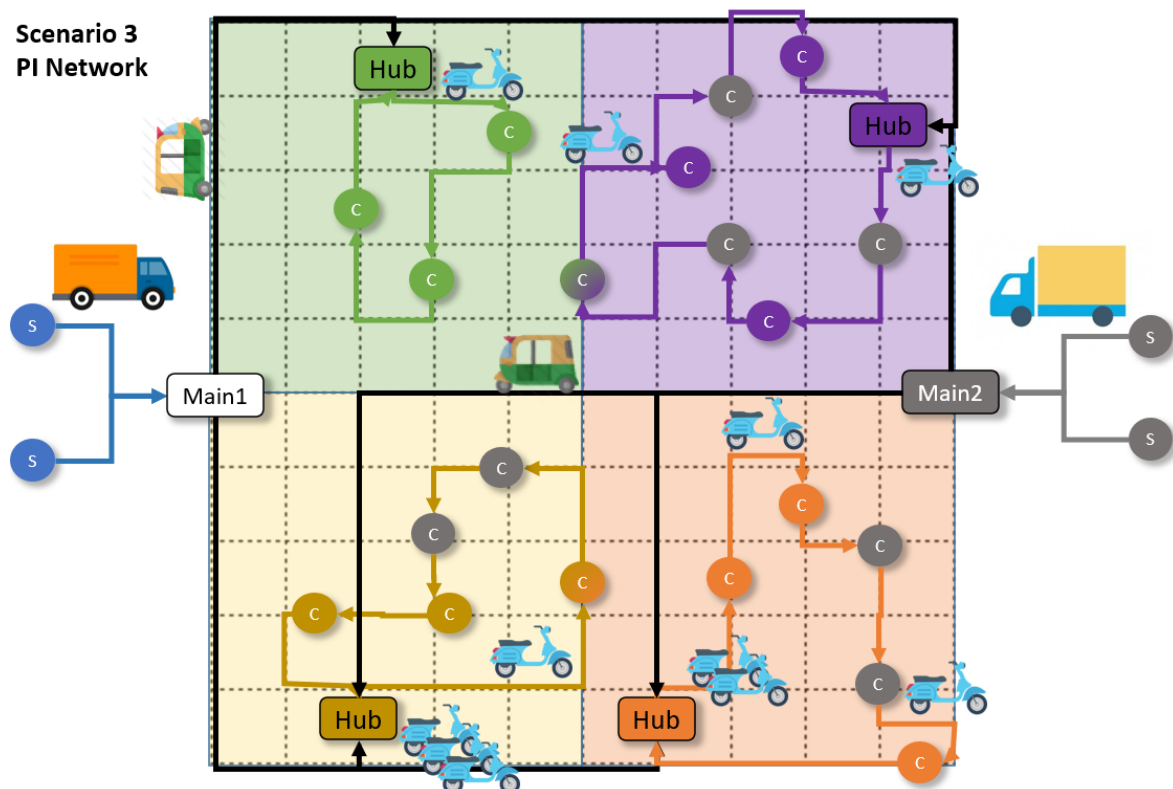


Figure 21: PI-oriented scenario #3, toward a PI network

The process of this scenario can be described as followed (see. Figure 22 and 23 below):

The PI network is used for horizontal collaborative transport in this step. In this manner, a request looks for a carrier to transport a shipment from one location to another.

In a PI network, carriers can use an open PI hub to exchange requests and optimize vehicle fill rates or reduce empty runs. The carriers are sharing information about the requests they have

on one hand and potentially coordinating to combine multiple requests into a single trip in order to improve transport efficiency and profitability on the other hand. This may involve one carrier taking on a request from another carrier if they have the capacity to do so, but the specifics will depend on the arrangements between the stakeholders.

Simply, just like routers route data packets in the digital internet, open PI hubs route freight in a physical internet network. This way, a request can be reallocated to the most appropriate and available carrier every time it arrives at a hub, and each reallocation is considered a local optimization.

The distinguishing feature of PI is that transport networks are organized and optimized in a decentralized manner, which means that the optimal route for a given request is updated every time it arrives at a PI-hub based on real-time and local information.

To effectively manage these decentralized systems, transport and collaborative protocols are necessary for the level of service and global optimization of the network. In addition, this interconnected and decentralized transport network can also help reduce inventory levels and improve city logistics efficiency.

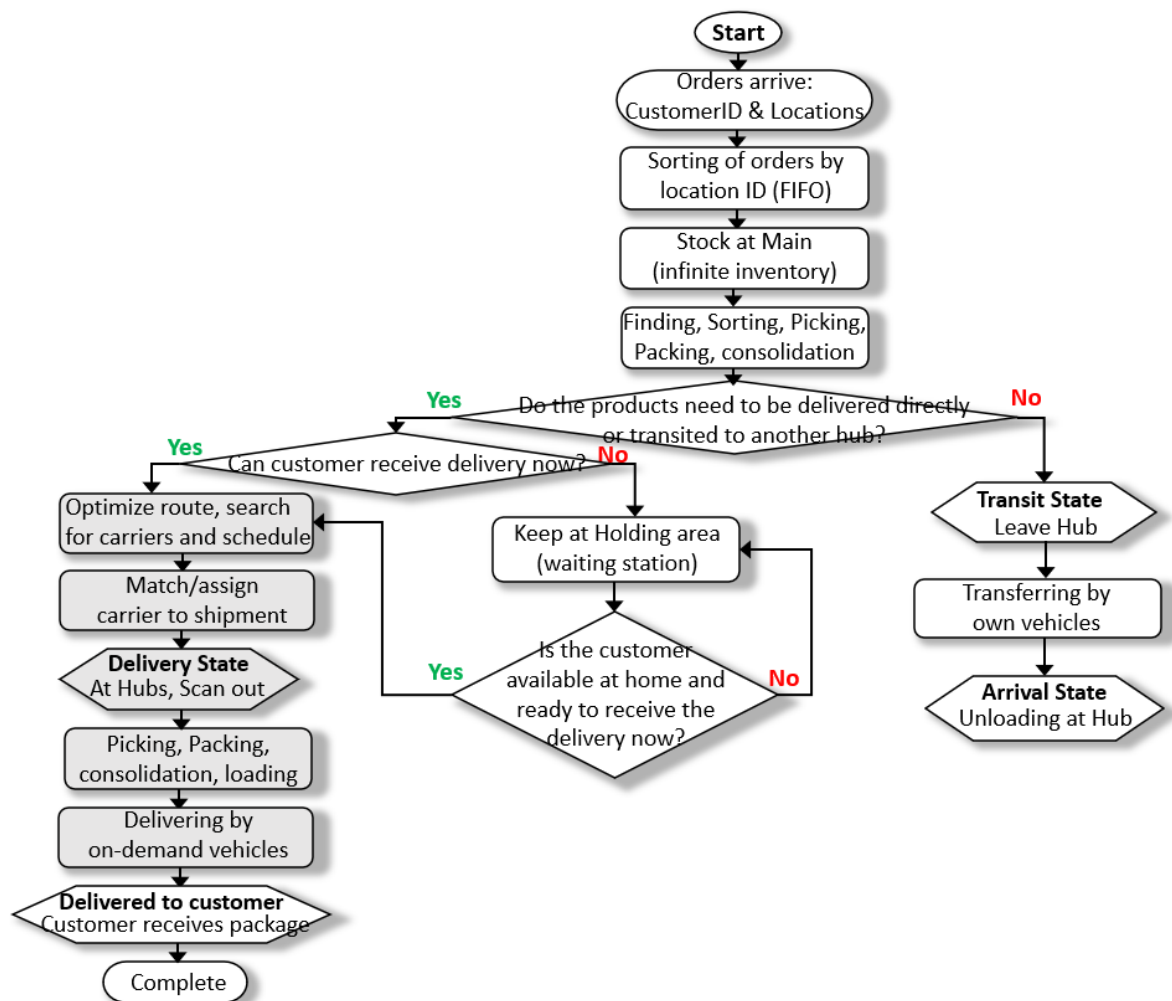


Figure 22: Main process of order fulfillment for the collaboration scheme of PI network

The step in the flowchart of both Figures 22 and 23, "Match/assign carrier to shipment" means that the open PI-hub has identified a carrier that is available and capable of delivering the shipment to the customer's location. The carrier may be notified to come and pick up the shipment or may already be scheduled to pick up the shipment based on the information shared by the open PI-hub. So, it can involve both calling the carrier and scheduling the pick-up. When a carrier is matched or assigned to a shipment, it means that all the necessary information has been shared and the carrier is aware of their pick-up and delivery schedule. When the time comes, they will pick up the shipment and deliver it to the customer.

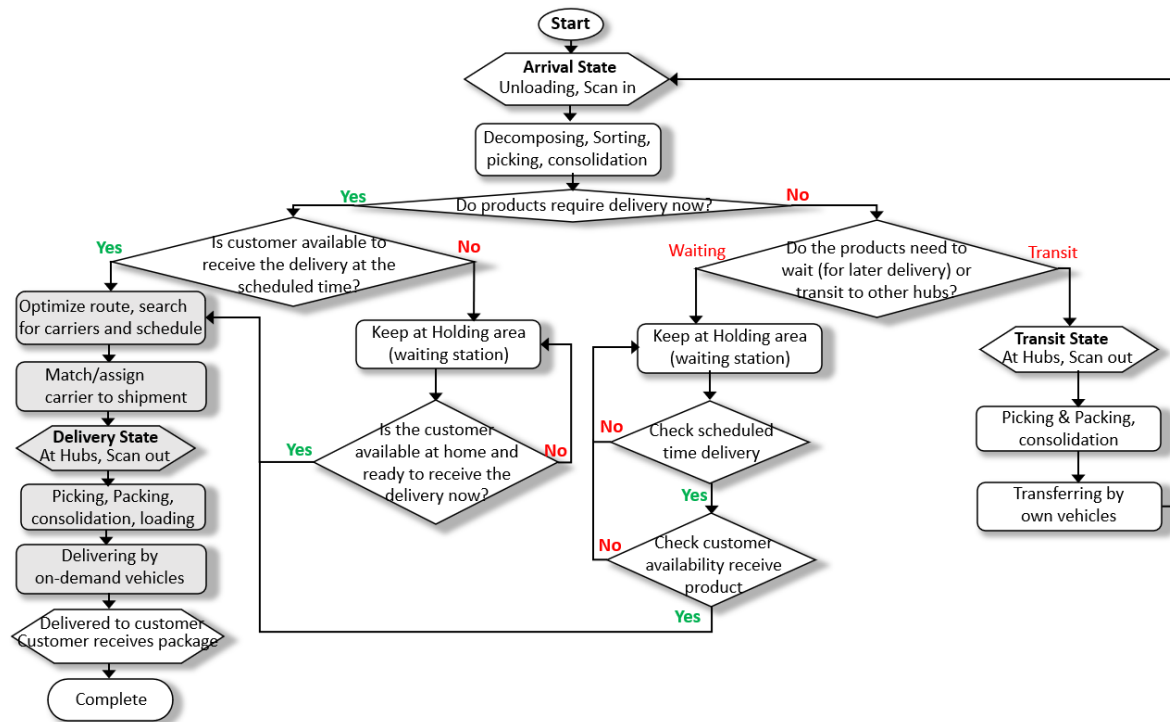


Figure 23: Hub process flow, customer fulfilments, considering collaboration scheme of PI network

CHAPTER IV. EXPERIMENT AND RESULTS

“You shouldn't do things differently just because they're different. They need to be... better”

~ *Elon Musk, the entrepreneur and founder of companies such as SpaceX and Tesla, (2013)*

It is now a question of presenting the details of the technical and conceptual choices which were made to support the definition of an experimental bench adapted to the resolution of our research problem.

In practice, this chapter discusses the different possible modeling approaches and justifies the decision to move towards a hybrid simulation model based on agent modeling and discrete event simulation.

Above all, we propose in the following a description of the characteristics of the implemented technical model, based on the contributions developed in Chapters 2 and 3, whether it is about data, parameters, variables and associated assumptions.

The presentation of a real industrial case and a set of key performance indicators used as a support for the tests ends the framework of the experiments.

Finally, and most importantly, the chapter presents all the numerical results obtained and discusses in this context the advantages and limitations of the proposals made.

1. Background on simulation modeling

Modeling is a technique used to address issues that exist in reality. Computational modeling is designed and used to optimize systems before they are put into practice when prototyping or experimenting with the actual system is too expensive or even impossible. It allows the process of mapping from the real-world problem to its model in the world of models such as abstraction, analytical, and simulation (Borshchev, 2013; Borshchev & Filippov, 2004).

The process of *abstraction* includes model analysis and optimization, and then mapping the solution back to the real system. We can distinguish between analytical and simulation models. *Analytical* is a static model in which the result is functionally determined by a set of input parameters. Such a model can be implemented using a spreadsheet or a Business Intelligence software for instance. However, in some cases, the analytical solution is not possible or it could be very difficult to find. Therefore, simulation as a dynamic modeling can be used as an alternative approach. Generally speaking, a *simulation* model may consider a set of guidelines, such as equations, flowcharts, and state machines, that determine how a system will model and change over time (in the future) based on its current state (Borshchev & Filippov, 2004). This set of rules is known as “executable”, telling how to obtain the next state of the system from the current state. So, simulation is the process of model “execution”, which takes the model through state changes over time, whether those changes are discrete or continuous. That means the simulation model gives the trajectory of the system in time. Typically, simulation modeling provides a better answer and a more effective solution when dealing with complex problems involving time dynamics (Borshchev, 2013). In this manner, there is no analytical solution regarding the complex system due to it is dynamic for instance causal and time dependencies and time-related constraints (see Figure 24 below) (Borshchev, 2007, 2013).

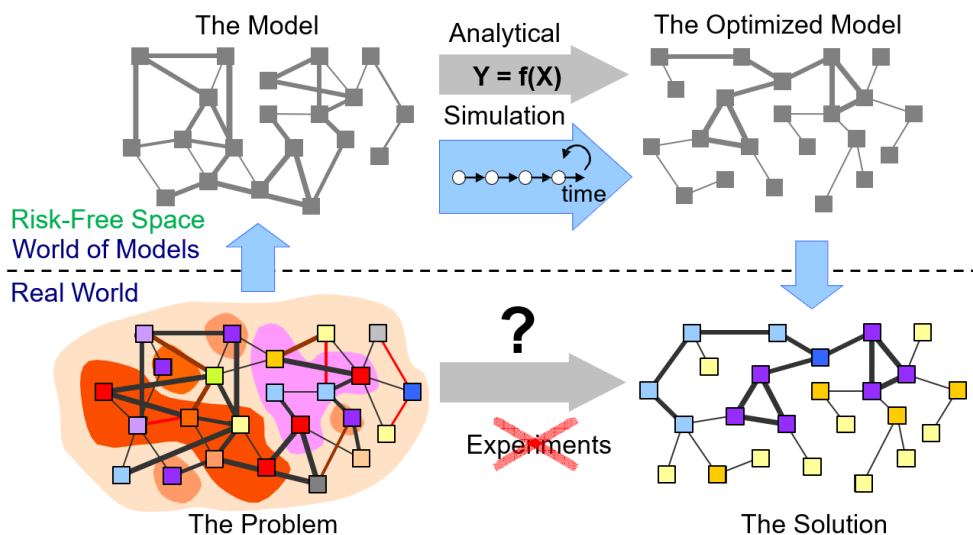


Figure 24: Risk-free virtual “world” of models (Borshchev, 2013)

Furthermore, the virtual modeling world is completely risk-free, unlike real-world systems (see Figure. 24). As a result of experimenting in this risk-free environment, we are able to develop and test the models using various system designs and provide answers to hundreds of hypothetical scenarios and “what-if” questions (Gorod et al., 2019; Suslov & Katalevsky, 2019).

Building a model is not enough after it is completed because it can be treated as a black box. So, it is about how we develop the simulation models and choose the abstraction level and methodology (Borshchev, 2007). Currently, three types of simulation modeling methods are utilized based on the level of abstraction (Borshchev, 2013). These include discrete-event simulation (DES) or process-centric by Geoffrey Gordon, 1960s (G. Gordon, 1978a, 1978b), system dynamics (SD) by Jay Forrester, 1950s (Forrester, 1968), and agent-based modeling (ABM) in 1990s by early seminal works (Epstein & Axtell, 1997, 1996; Gilbert, 1997).

SD focuses on describing the entire process as a whole and is typically used to study systems that have a high level of abstraction. This method may be used to examine the connection between the accumulating parts of a system or its surroundings (called "stocks") and the flows that occur between them, based on physical laws. This type of modeling can help in understanding and predicting changes in a system, even when data is missing (Borshchev, 2013).

The basic concept of DES is to study the system as a series of actions, which is a process sequence of operations performed across entities. Furthermore, depending on the specific details of a project or organization, the best simulation method can be selected and used on a case-by-case basis (Suslov & Katalevsky, 2019). DES is a process-based approach that investigates how a system changes over time after events occur. It works best in situations that require medium-level details, a tactical level, and a middle level of abstraction. DES is commonly used to investigate issues such as resources, flowcharts, and/or transportation, how to optimize warehouse dimensioning, the effect of machine breakdowns on production, (Borshchev, 2013) and call center flow problems (Petitdemange, 2020).

Last method, ABM system uses a bottom-up approach (or called "bottom-up modeling"), which is characterized by interacting objects with their own behaviors. The overall behavior of the system emerges as a result of the actions of each individual agent (Suslov & Katalevsky, 2019). Typically, ABM could be defined as the behavior at individual level of agents, and the global behavior emerges as a result of the actions of many (tens, hundreds, thousands, millions) of these agents, each following its own set of behavior rules. The agents live and interact (direct or indirect interaction) with each other and their environment. This is why ABM is also referred to as bottom-up modeling, because it starts by focusing on the behavior of individual objects and builds up to understanding the overall system behavior (Borshchev & Filippov, 2004). Agent-based models can be used to simulate very detailed systems or operational scenarios, as well as high-abstraction level systems where agents can represent companies, vehicles, pedestrians or governments (Borshchev, 2013).

We may concentrate on using SD and DES at the "System Level" to analyze the overall behavior of the system that interacts between different components and how they influence each other over time. In the meantime, we can use ABM to be "Individual-Centric" to think about how different agents behave over time and how their interactions with one another impact the behavior of the system as a whole. As an alternative, we can use SD for "Continuous and Aggregated" to study systems with many components that change continuously. Subsequently, DES and ABM could be used together to conduct "Discrete and Disaggregated" analyses of systems that change discretely and are made up of smaller parts. For example, DES simulates the sequence of events that occur in a system, whereas ABM simulates the behavior of individual agents (Borshchev, 2007).

There are no workarounds. Each of these methods has advantages and disadvantages depending on the usage and application (Ghadge et al., 2022). SD is the most appropriate approach for assessing such complex interactions (Forrester, 1968, 1987; Sterman, 2001, 2010). In practice, if you feel the SD abstraction level (stocks, flows, feedback dynamics) is enough and sufficient for the problem, use aggregated view (Borshchev, 2007, 2013; Ghadge et al., 2022). If the system can be naturally represented as a process (sequence of operations, entities, resources), using DES is probably more adequate (Borshchev, 2013; S. C. Brailsford et al., 2019; G. Gordon, 1978a; W. Hu et al., 2023). Finally, if we are more comfortable with specifying individual behavior of objects (people, vehicles, companies, assets, projects, etc.), using ABM is more appropriate and helpful in these cases (Axtell & Farmer, 2022; Borshchev, 2013; de Bok & Tavasszy, 2018; Hussein et al., 2023; Labib & Watfa, 2023).

To summarize these three different approaches (SD, DES, and ABM) for resolving the complex real-world system, we might deal directly with abstraction levels and, more importantly, how we look at the problems (Borshchev, 2013). Several studies (Borshchev, 2007, 2013; Suslov & Katalevsky, 2019) suggested that there are two important points according to these methods (SD, DES, and ABM). First, we can easily vary the level of abstraction and viewpoint until it perfectly fits the problem. Second, we can mix different methods in one model; for instance, multi-method or hybrid simulation modeling has been applied recently by several studies (Grest, 2022; Moradkhani et al., 2022; Roci, Salehi, Amir, Asif, et al., 2022; Roci, Salehi, Amir, Shoaib-ul-Hasan, et al., 2022).

The choice of the simulation method for a system depends on the objectives and questions of the model that the simulation aims to address. When dealing with complex systems (often real-world problems), it can be beneficial and often useful to incorporate multi-method techniques by considering the complementary capabilities of each method while also being aware of their respective limitations (Borshchev, 2013). Additionally, the multi-method approach is more adaptable and flexible in dealing with the dynamic natures of complex systems, as each of these modeling approaches serves a specific range of abstraction levels (Roci, Salehi, Amir, Asif, et al., 2022; Roci, Salehi, Amir, Shoaib-ul-Hasan, et al., 2022). Furthermore, they cover different behaviors based on simulation time and state changes of the modeled system. For example, SD is a continuous-time approach, which the state of the model changes gradually over time. On the other hand, DES and ABM are discrete-time approaches, which state changes happen at specific moments (or discrete points) in time as a result of a specific event (Borshchev, 2013; Roci, Salehi, Amir, Asif, et al., 2022).

2. The proposed model

Hybrid simulation (multi-method simulation modeling) has experienced near-exponential growth in popularity over the last two decades as a modeling technique that combines two or more methods such as DES, SD, and ABM (S. C. Brailsford et al., 2019; Roci, Salehi, Amir, Asif, et al., 2022; Roci, Salehi, Amir, Shoaib-ul-Hasan, et al., 2022; Swinerd & McNaught, 2012). In this work, we will use this technique to assess PI through a set of proposed scenarios for city logistics in developing countries to capture their complex and dynamic nature (see previous Chapter).

The following section explains in detail how to build a multi-method simulation model for city logistics in order to evaluate key performance indicators (KPIs) in the perspective of economic, environmental, and technical performance for better decision-making. The proposed method is implemented in real-case scenarios in developing countries for city logistics.

To model and simulate the city logistics of a developing country, three critical factors need to be considered (see the Figure 25 below):

- A multimethod simulation model architecture is proposed for PI-oriented city logistics in developing countries (PIOCLDC), where the heterogeneous characteristics of stakeholders are modeled individually as autonomous agents using techniques such as ABM and DES. ABM is implemented to capture the dynamic behavior of city logistics stakeholders. The uncertain interactions between their internal activities and resources are modeled using DES.
- A geographic information system (GIS) defines an agent environment in order to establish connections based on the geographic locations of the agents (such as OpenStreetMap, latitude and longitude of agents, etc.).
- The last-mile delivery of product flows is developed through interactions among various stakeholders in the network, which is the order lifecycle process for each scenario.

The SD approach is not considered suitable for the system under study because it ignores the low level of details of each stakeholder's internal processes (Hussein et al., 2022), and the focus of this study is not on feedback loops, which is one of SD's main features. All products are assumed to be in stock at the central warehouse (infinite inventory).

Unlike SD, the suggested modeling method combines the use of two simulation techniques, ABM and DES, in order to account for the unique aspects of the PI-oriented city logistics system in developing countries. ABM is a more recent simulation method when compared to Monte Carlo simulation, DES, and SD. ABM uses a bottom-up modeling approach, which means that the behavior of individual agents must be defined first, and then the overall system behavior results from the interactions between these agents (Borshchev, 2013).

The best ABM simulation method for modeling systems includes the following features: 1) a moderate number of agent types; 2) complex interactions between agents; 3) heterogeneous agents, which means that each agent within the same type may have different characteristics and parameter values; 4) changing system states over time; and 5) adaptive agents, which can learn from previous actions and adjust the next ones accordingly (Rand & Rust, 2011). As a result, ABM is becoming more popular as a modeling tool for logistics and supply chain systems (Lee

& Kim, 2008), for instance, healthcare (Isern & Moreno, 2016), traffic and transport systems (B. Chen & Cheng, 2010), and different applications in the construction field (Khodabandelu & Park, 2021), e.g., construction supply chain (Du et al., 2017), workers-management interactions behavior regarding workers' safety (P. Zhang et al., 2019), tower crane operations (Younes & Marzouk, 2018), and the productivity of robotic 3D printers (Abou Yassin et al., 2020). Recently, (Axtell & Farmer, 2022) highlighted the use of agent-based modeling in economics and finance and presented how it can be used to relax conventional assumptions in standard economic models. In this study, ABM is used to model the different behaviors of vehicles as stakeholders and their complex interactions in the city logistics of developing countries.

However, it is difficult to model the internal processes of each agent using ABM. Each process involves a sequence of operations where a set of resources provides services to passive entities. When these entities compete for a limited set of resources in an operation that requires time, queues form in the system. DES is capable of accurately representing the sequence of operations, the complex interactions between resources and entities, any queues that form, and the uncertain duration of operations. With DES, the system is depicted as a sequence of operations represented in a flowchart structure. In general, the process starts with a source block that generates system entities and ends with a sink block after a series of operations that require various resources. If these resources are not immediately available, these entities may have to wait for service. Furthermore, DES has been widely used to model processes within agents (Borshchev, 2013). Because of its simplicity, this method has been used in several studies, including supply chain and logistics (S. Brailsford et al., 2014; Grest, 2022; Hussein et al., 2023; Tako & Robinson, 2012) and healthcare (Petitdemaille, 2020; Vázquez-Serrano et al., 2021). As a result, in this work, we will use DES to model the processes of stakeholders.

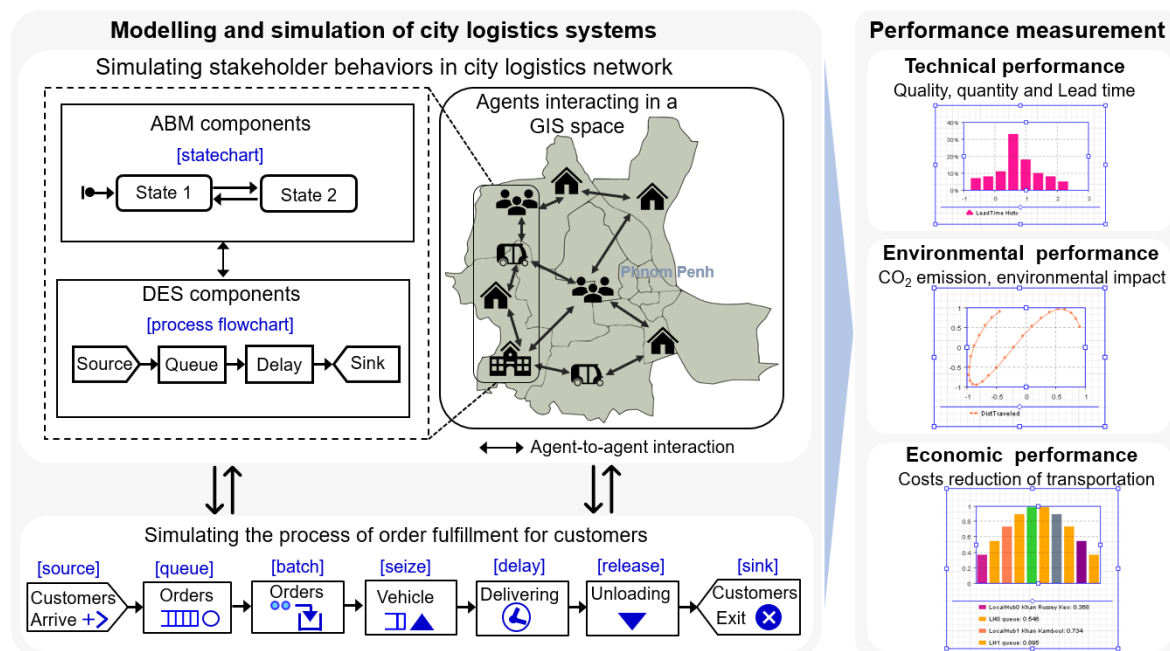


Figure 25: Simulation modeling of city logistics using multiple methods in developing countries.

The simulation model of PI-oriented city logistics in developing countries is created by following the general steps for building an ABM simulation as outlined by (Macal & North, 2017a, 2017b) and shown in Figure 26 below.

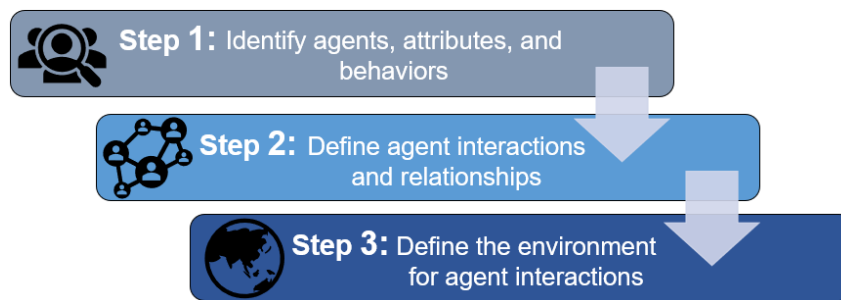


Figure 26: Three steps for building an ABM simulation (Macal & North, 2017b)

The first step is to identify the different types of agents, their attributes and behaviors, including all relevant stakeholders involved in the concurrent processes of the entire order fulfillment lifecycle. These stakeholders are modeled as individual agent types, such as order processing at the main hub and local hub, delivery vehicles, and the customer. Agents' behavior can be described in different manners. Typically, an agent has a notion of state, and its actions and responses are based on that state. In this case, the behavior can be defined by using statecharts (Borshchev, 2013).

Statecharts in ABM are a tool to simulate events and time-driven behavior to represent various discrete actions. In some cases, using a DES or SD approach may better capture the internal dynamics of an agent (Borshchev, 2013). In these cases, a DES process flowchart is placed inside the agent. However, SD is not used in this study, as mentioned above. The process flowcharts in DES modeling help delineate the steps involved in operations for entities like resources providing delays and services. This study proposes using a combination of ABM and DES process flowcharts to better understand the behavior of the diverse stakeholders involved in the city logistics in developing countries. The simulation of a stakeholder in supply chain and logistics activities, represented as an agent, can be done using a DES modeling approach that focuses on a process view of the system (S. Brailsford et al., 2014; S. C. Brailsford et al., 2019).

For instance, a 'DE source' block can trigger orders from customers to start order fulfillment processing 'DE enter' block at the Main Hub as well as 'DE enter' block at the Local Hub. Following that, an 'AB statechart' receives a message for a delivery and states the movements of vehicles in GIS space from one location to another, as well as the delivery process activities. This 'AB statechart' depends on sequence operations of DE state of queue, batch, seize, delay blocks. These DE states impact the 'AB statechart' state and vice versa.

The characteristics and behaviors of agents in the model can be described by a set of attributes and methods. In an ABM, an attribute is a variable of a specific type (e.g., integer, double, string, or boolean) that represents a specific characteristic of the agent, such as its location, capacity, delivery lead time, and so on. A method is a set of instructions that performs a specific task and defines the agent's behavior, such as defining a method to calculate lead time or CO2 emissions. This method will be executed when the simulation runs, based on the information available about the agents and their behavior.

The second step is to specify how agents interact and their relationships with each other. This could be done by designing the interface of the agent to allow for interaction with other agents and external components of the model (Borshchev, 2013). The agent's interface is a collection of features that can be accessed and used to communicate with the agent, such as attributes, methods, ports, and messages.

The third step consists in defining the environment in which agents exist (live) and interact with each other (other agents). This work employs a GIS space type to integrate PI-oriented city logistics stakeholder agents into a geospatial environment defined by a GIS map, which is more useful and appropriate for placing agents in a specific context. The geographical location of stakeholders is critical in establishing connections based on the agents' locations. Agents can also traverse the transportation network depicted on the GIS map, moving from one location to another at a specified speed, within the GIS topology. This allows us to accurately determine the actual distances traveled between stakeholders, resulting in more accurate estimates for transportation costs and CO2 emissions (Borshchev, 2013; Roci, Salehi, Amir, Asif, et al., 2022; Roci, Salehi, Amir, Shoaib-ul-Hasan, et al., 2022).

To sum up as shown in the below Figure 27, the proposed multi-method simulation technique aims to reflect the system behavior that emerges from the intricate interplays among the various stakeholders involved in city logistics in a developing country.

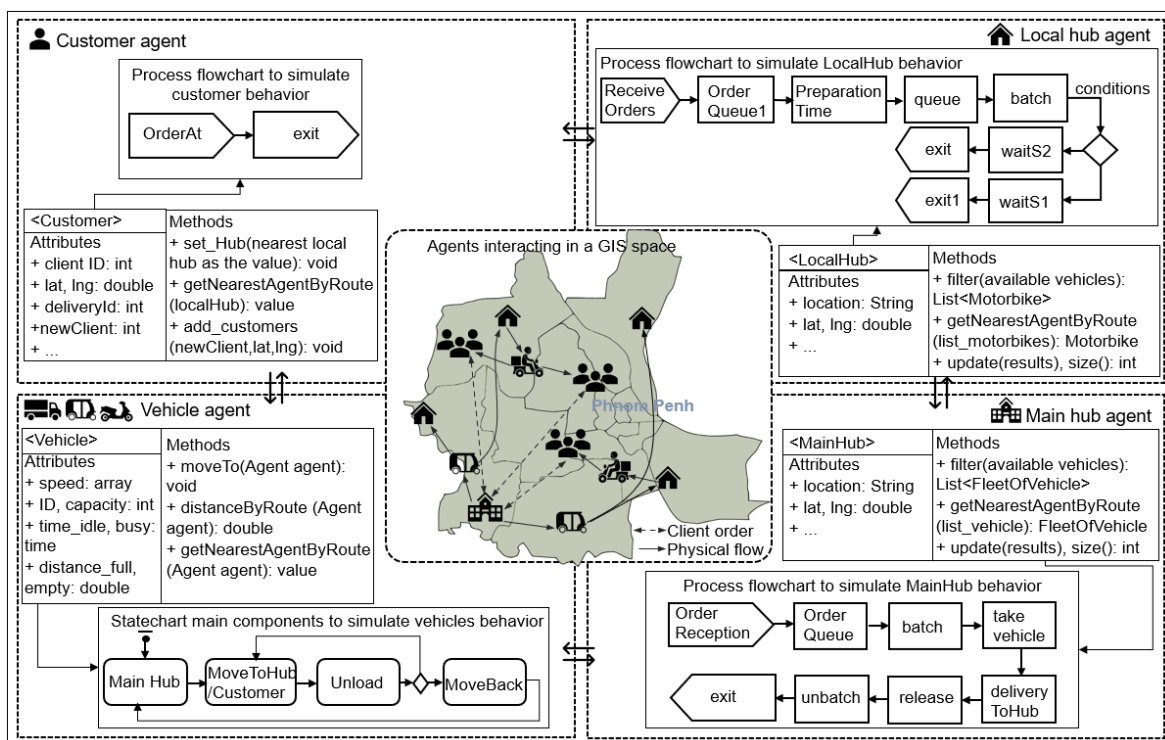


Figure 27: Multi-methods model for PI-oriented city logistics.

2.1. The agents

2.1.1. The Customers

The role of customer agents is responsible for generating orders based on the data file which is embedded to model through “OrderAt” block. The behavior of customers in the model is simulated using a DES under the Customer agent, as shown in Figure 27. The attributes and methods used to define the Customer agent are incorporated into the DES technique. The "OrderAt" block holds the details of the order data file and triggers the simulation process. The customer's GIS location is indicated in the database table, for instance, by latitude (lat) and longitude (lng). It is important to note that two Customer type agents share the same parameters and behavior, however, they may vary in factors such as location. That means two agents of the same type (e.g., in this case, two customer agents) can differ in some details for instance latitude and longitude and etc.

Table 2: Main attributes and methods of the Customer agents

| Type | Name | Description |
|------------|---|--|
| Attributes | clientId: int | Unique customer identifier number of type integer |
| | lat, lng: double | The customer's location is loaded from the latitude and longitude in a GIS space. |
| Methods | set_Hub(nearest local hub as the value): void | This method sets the Hub attribute of the agent object to the nearest agent by route to the specified localHub. It takes the nearest agent as input and does not return anything (void). The “set_Hub” method sets the value of the Hub attribute of the agent object. The value passed to the set_Hub method as an argument is the nearest local hub to the agent, which is determined by calling the “getNearestAgentByRoute” method. |
| | getNearestAgentByRoute(localHub): value | This method takes a localHub parameter twice and returns the nearest agent by route to that hub. The first time it is called, the nearest agent object to the localHub parameter is assigned to the Hub property of the agent object. The second time it is called, the same nearest agent object is passed as an input parameter to the set_Hub method of the agent object, so that the method can access and use the agent object to perform the necessary operations. |

| | | |
|--|---|---|
| | <code>add_customers(newClient,lat,lng): void</code> | <p>This method adds new customers to the simulation by providing the necessary information in the data file from the database such as the new client's ID, latitude, and longitude. This means, it takes a <code>newClient</code> parameter, as well as <code>lat</code> and <code>lng</code> parameters specifying the latitude and longitude of the new customer. It adds the new customer to the customers object and does not return anything (void).</p> |
|--|---|---|

2.1.2. The Main Hubs

The Main Hub agent is represented by one company that processes customer order fulfillments in the city. This agent is responsible for managing delivery processing based on set rules for proposed scenarios, where orders are generated from customer orders. The Main Hub agent is modeled using a DES modeling approach to deal with customer orders (e.g., Scenario 0), Local Hubs (e.g., Scenario 1 and 2) and logistics processes. The Main Hub agent's behavior is identified by applying attributes and methods to the DES process flowchart shown in Figure 27.

Table 3: Main attributes and methods of the Main Hub agents

| Type | Name | Description |
|------------|--|--|
| Attributes | location: string | Location of Main Hub of the type text string. |
| | lat, lng: double | The latitude and longitude attributes represent the location of the Main Hub in GIS space. |
| Methods | filter(main.fleetOfVehicles agent): List<FleetOfVehicle> | The filter method filters a list of FleetOfVehicle objects and returns a list of vehicles that are in the state of "AtDistributor" (statechart's state name) and are not busy. It searches the available vehicle. |
| | getNearestAgentByRoute(list_mb): FleetOfVehicle | The method is used to find the closest FleetOfVehicle from a list of filtered FleetOfVehicle objects. The method takes a list of filtered FleetOfVehicle as input and returns the one that is closest to a specific location. |
| | size():int | This method is checking the size of the filtered list of FleetOfVehicle objects returned by the filter method. The filter method filters the list of all FleetOfVehicles and returns a list of vehicles whose state is "AtDistributor" and are not busy. If the size of the filtered |

| | | |
|--|--|--|
| | | list is equal to 0, the code returns 1. If the size is greater than 0, it returns 0. |
|--|--|--|

2.1.3. The Local Hubs

The Local Hub Agent serves as a cross-docking hub for efficient delivery services. This agent is tasked with exchanging transportation (such as trucks, Tuk-Tuks, and motorbikes) and managing delivery processing based on the proposed scenarios. The Local Hub agent's behavior is recognized by applying attributes and methods to the DES process flowchart shown in Figure 27.

Table 4: Main attributes and methods of the Local Hub agents

| Type | Name | Description |
|------------|--|---|
| Attributes | location: String | The name or address of the local hub. |
| | lat, lng: double | The latitude and longitude coordinates of the local hub. |
| Methods | filter(main.motorbikes,m->m.statechart.getState().name()=="MovingSomewhere" && m.busy==0): List<Motorbike> | This method filters a list of Motorbike objects from the main.motorbikes list, and returns a list of only those motorbikes whose statechart's current state is "MovingSomewhere" and they are not busy (busy == 0). |
| | getNearestAgentByRoute(list_mb): Motorbike | This method takes a list of filtered Motorbike objects as input, and returns the motorbike that is closest to a specific location (presumably the LocalHub's location). |
| | filter(main.fleetOfVehicles,m->m.statechart.getState().name()=="AtDistributor" && m.busy==0 && m.center==this): List<FleetOfVehicle> | This method is checking if there is a "FleetOfVehicle" in the "main.fleetOfVehicles" list that is in the state "AtDistributor", is not busy (busy=0) and is at the center (center==this). If there is no such vehicle in the list, the method returns 1. If there is at least one vehicle that fits the criteria, the method returns 0. |
| | size(): int | This method returns the number of elements in the list. The method returns an integer value. |

2.1.4. The Vehicles

Vehicle agents are responsible for delivering products from the Main Hub and Local Hubs located at GIS locations to customers' homes and residential buildings. Small trucks (vans), tuk-tuks, and motorbikes are used as vehicle fleet agents in this modeling setup. The efficient delivery of ordered fulfillments and optimal use of the delivery fleet can only be achieved by effectively managing and altering these agents, particularly with regard to the sequencing methodologies being tested.

Typically, vehicle agents are called for dispatches based on delivery demands (collections of customer orders) sent through the Main Hub and Local Hub agents. For example, the Main Hub may require trucks to send products to Local Hubs, while Local Hubs may need tuk-tuks or motorbikes to forward these products to customers based on the specific order details, time, and location. These vehicle agents pick up assigned deliveries from the Main Hub and Local Hub(s) locations, transport the goods to customer locations, and return to their initial position and state in the GIS space. They wait for new tasks (e.g., scenarios 0 and 1) if no immediate assignments are scheduled for them, or go somewhere else (e.g., scenario 2 considering on-demand vehicles).

To simulate the behavior of vehicle agents during the process of dispatching products for request order fulfillment, a set of attributes relevant to characterizing the various types of vehicle agents must first be defined. Basically, the simulation model has three types of vehicle agents: trucks, tuk-tuks, and motorbikes. These agents may have similar attributes and methods, but they serve different purposes. Trucks are used for transporting packages from the Main Hub to Local Hubs, while tuk-tuks and motorbikes are used for delivering packages to customers. The methods used by these agents vary based on their specific role in the simulation. A detailed list of the attributes employed to simulate the vehicle agents is reported in the Table 5 below.

Table 5: Main attributes and methods of the vehicle agents

| Type | Name | Description |
|------------|--------------------------------|--|
| Attributes | ID : int | Unique vehicle identifier number of type integer |
| | Speed: array | The speed attribute is of array type. It would store multiple values, which could represent the speed of the vehicle at different times or under different conditions (e.g., the conditions of road, traffic, vehicle types and etc.). |
| | center: MainHub, Local Hubs | The centre parameter represents the Main Hub, Local Hubs agent to which the vehicle agents is assigned. Essentially, the "center" parameter stores a reference to a Main Hub and Local Hub agents object, allowing us to access information about the Main Hub and Local Hub agents and interact with it from within these vehicle agents. |
| | Capacity: int | Capacity can store integer values. By setting the capacity as an int type parameter, we can control the capacity of the vehicles in our simulation model and use this information to make decisions and model the behavior of the system. |
| | Loaded: double | Loaded set to a data type of double, which means it's a variable that can store decimal values. The load capacity of the vehicle agents, or the amount of goods it is carrying. |
| Variables | order: BatchForHub, OrderBatch | The order variable represents a batch of orders that are to be delivered by the truck agent, and the type of this variable is an instance of the BatchForHub agent. |
| | Last_time: date | This variable represents a date and time value. The value stored in this variable will be used to keep track of |

| | | |
|---------|---------------------------------|--|
| | | the last time the truck performed a task, such as making a delivery. |
| | dist_empty: double | distance_empty is a numerical value that can hold decimal places. This variable represents the distance travelled by the truck when it is empty (return). |
| | dist_full: double | distance_full represents the total distance that the truck has traveled while it is loaded with goods. The type of this variable is set to double, indicating that the value stored in this variable is a decimal number. |
| | time_busy: time | The time_busy represents the duration of time that the truck is occupied or busy with a delivery task. The value stored in this variable will represent a time duration, which is a measure of how much time the vehicle has been actively engaged in delivery tasks or other productive work. |
| | time_idle: time | The time_idle represents the amount of time the truck has been idle, or not performing any tasks. The type "time" is used to indicate that the variable is representing a duration of time. The value of this variable can be used to measure the efficiency of the truck and its utilization over time. |
| Methods | moveTo(): void | The "moveTo()" method is used to move an agent to a specified location, such as a truck agent, to move from Main Hub to Local Hubs in this case. This allows for the modeling of movement in a simulation. |
| | distanceByRoute(): double | distanceByRoute() is used to determine the distance between two points along a specific route. This method allows for the calculation of the distance taking into account the specific path that the vehicle agent must follow. |
| | getNearestAgentByRoute(): value | The "getNearestAgentByRoute()" method finds the nearest agent to a specified route. It returns the nearest agent from the current vehicle agent's position to the specified location (e.g., the nearest LocalHub for the truck). This method calculates the shortest path based on the routing information, using the route network in the simulation. |
| | date(), getTime(): date, double | The "date()" and "getTime()" methods are used to retrieve the current date and time, respectively. |
| | setSpeed(): void | The "setSpeed()" method sets the speed at which an agent moves. |
| | size(): integer | The "size()" method returns the size or number of elements in a collection. |
| | filter(): list of Order objects | The "filter()" method is used to filter a collection based on specified conditions. |
| | send(): message or object | The "send()" method sends a message or signal from one agent to another. |

2.2. Connection between the agents

2.2.1. Overall architecture

In our model, the agents previously described are used as stakeholder-agents for the simulation process, they collaborate and interact with one another while performing their assigned tasks (see the Figure 28 below).

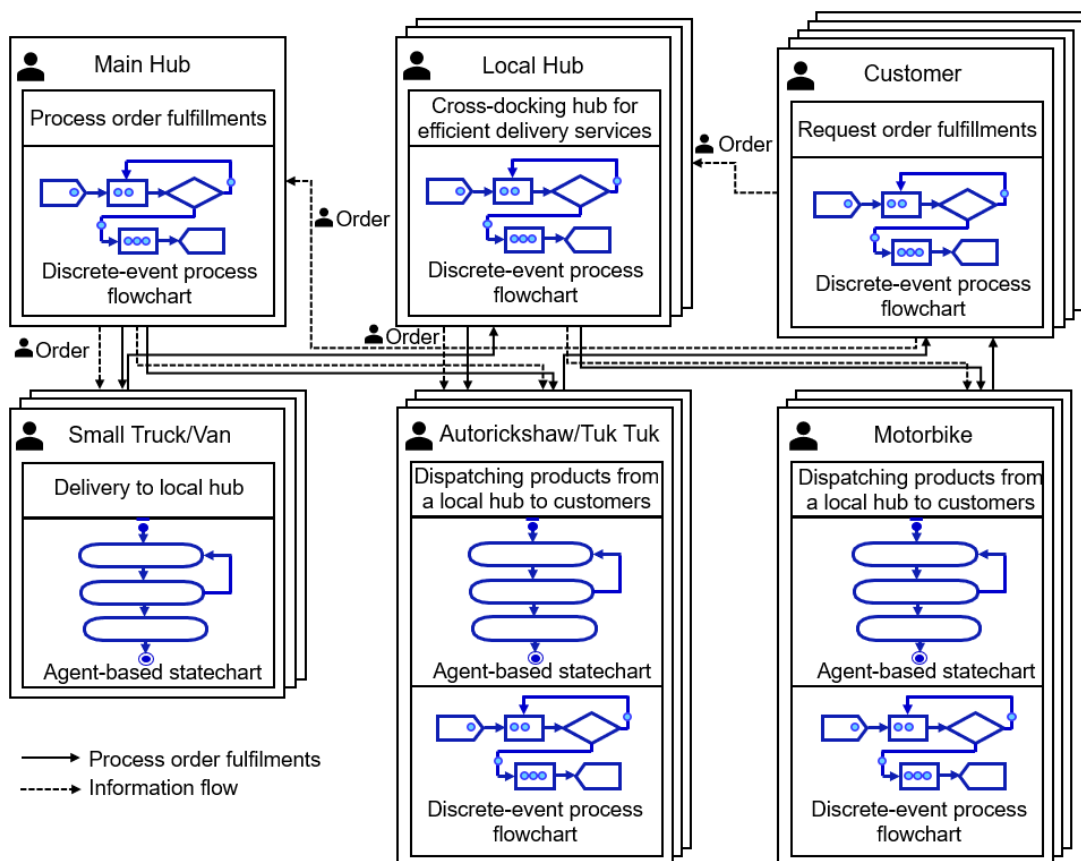


Figure 28: Overview of the multi-method simulation model of PI-oriented city logistics in developing country.

In our model, the order agent serves as the intermediary responsible for facilitating communication between stakeholder agents, thereby simulating the flow of information. In the last-mile delivery process, the methodology begins when customers place product orders.

An order is characterized by a unique identification number “Id_number”, a date of order when a specific customer demands for something. The order agent includes the information about the customers who have placed the orders and have a delivery scheduled. The main hub agents then receive the orders and start the process of order fulfilment as described on the following Figure 29.

Order batch agent is a type of agent that groups together multiple individual customer orders into a single batch, allowing for more efficient handling and processing. This could be useful in scenarios where it is more efficient to process multiple orders at once, rather than handling each order individually. The order batch agent could be responsible for determining which orders should be grouped together, and for managing the delivery of the grouped orders.

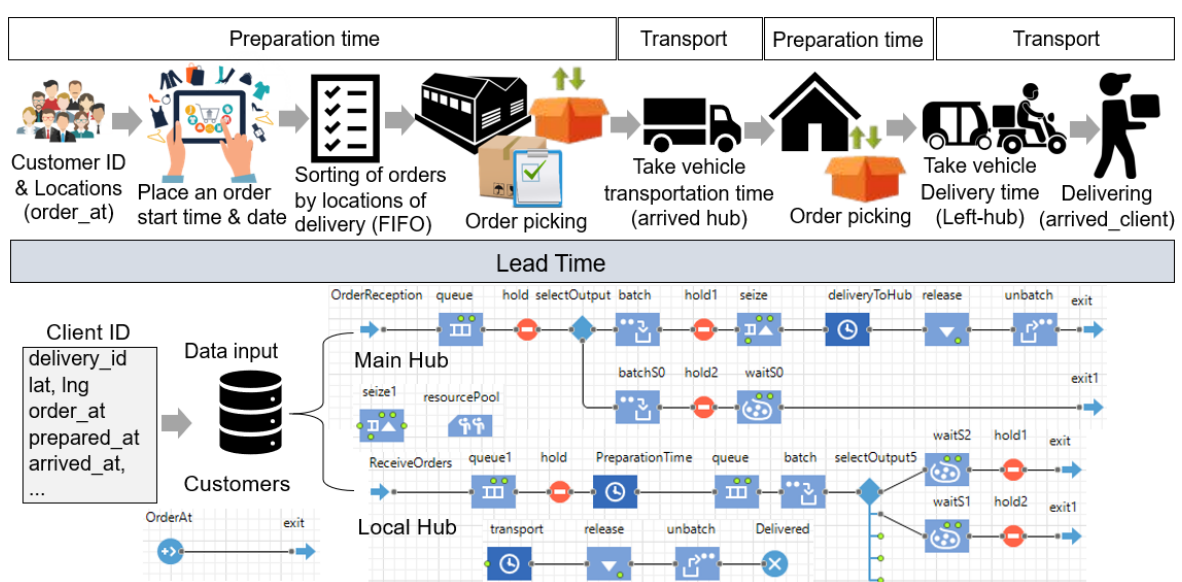


Figure 29: Life cycle of an order.

This agent is in charge of communication and information flow between customers and other relevant agents, such as Main Hub and Local Hub agents. It contains information about the customer order, such as the items being ordered, the delivery location (latitude and longitude), and the desired delivery time (start, prepare, and arrive). Table 6 provides the list of parameters that have been used as inputs to our simulation model.

Table 6: List of parameters of order agent for the simulation

| Parameter | Type |
|-------------------|---------|
| Id_number | integer |
| order_at | date |
| client_Id | integer |
| ship_time | date |
| arrived_hub | date |
| leave_hub | date |
| arrived_client | date |
| distance_traveled | double |

2.2.2. The process and model evaluation

2.2.2.1. General process

The process for fulfilling customer orders starts with the customer placing an order with the Main Hub. After receiving the order, there is a 1-hour preparation time at the Main Hub to get everything ready to be shipped. To optimize the transportation process, orders are grouped together in batches based on the First-In-First-Out (FIFO) rule and the capacity of the transport means. If the order falls under scenario 0, it is directly sent to the customer. However, if it falls under scenario 1 or 2, it is redirected to the Local Hub assigned to the customer, which acts as an intermediary cross-docking platform before the final delivery.

In the simulation, the customer orders were read from an external excel file that contained various parameters such as Client ID, latitude, and longitude, Delivery ID, Order At, Prepared At, and Arrived At. These orders are created when the order is placed with its parameters. These parameters were stored in the Order agent of the simulation, which helped to keep track of the order details. Additionally, the customer (or customer agent) link was created based on the same excel file, which made it easier to manage the orders and the corresponding customers. The time of wait (waiting time) before the batch (batch of multiple orders) is sent, even if it is not full, was considered into the simulation. This helped to optimize the delivery process and ensure that the orders were delivered on time. Finally, the preparation time was also taken into account, which included the time taken at the Main Hub and Local Hub. Overall, by considering these parameters, we were able to create a comprehensive simulation model that accurately reflected the real-world logistics system.

To measure the performance of the delivery in each scenario, we consider two types of distance for each vehicle: distance when full namely "Distance full" (with packages) and distance when empty call "Distance empty" (without packages or empty vehicle).

With this last-mile delivery model, there are three types of vehicles: trucks, tuk-tuks, and motorcycles. Each vehicle is timed and categorized according to whether it is delivering a parcel or sitting idle. "Time_idle" refers to the time when the vehicle is not delivering a parcel, while "Time_busy" refers to the time when the vehicle is delivering a parcel, even if it is empty. It means that whether the vehicle is carrying a full load or is empty (empty vehicle from a returned trip to the main hub or local hubs), in both cases, the vehicle is still considered busy during the delivery process. So, "Time_busy" refers to the duration of time during which a vehicle is engaged in delivering a parcel. Even if the vehicle is empty during the delivery, the time spent delivering is still counted as "Time_busy".

After defining the idle and busy times, we can consider the resource occupancy rate, which allows us to measure not only the time of utilization but also the volume used. Indeed, we have the Time_idle and Time_busy for each vehicle. And we also have the information if the batch is full or not. The model is programmed to keep track of the batch size and whether it has reached its maximum capacity or not. This information can then be used to determine the resource occupancy rate for each vehicle.

Furthermore, an important aspect of this work is the measurement of the LeadTime function. The LeadTime is calculated for each order, which is the time between the "order_at" timestamp of the order and the "arrived_client" timestamp (see Figure 29).

2.2.2.2. Delivery from Main Hub to Customer (Scenario 0)

The batch of orders is delivered using a single type of vehicle. The vehicle follows the First-In-First-Out (FIFO) rule for the batch, delivering each order in the order that it was received. Once all orders in the batch have been delivered, the vehicle returns to the Main Hub, ready for the next batch of orders. This ensures that orders are delivered efficiently and effectively, with a clear and organized process for handling the delivery of each batch.

This Scenario is the interaction between Main Hub and Customers. The total distance takes into account both the distance full (vehicle filled with packages) and distance empty (return trip of

the vehicle). For example, in this scenario 0 where M is the Main Hub and C is a customer, with a delivery capacity of n in this case, the total distance can be calculated as follows:

$$Distance_full = M_1C_1 + (C_1C_2) + (C_2C_3) + (C_3C_4) + \dots + (C_{(n-1)}C_n)$$

$$Distance_empty = C_nM_1$$

Where: Distance_full: the total distance travelled by the delivery vehicle when it is fully loaded. Distance_empty: the total distance travelled by the delivery vehicle when it is empty (see the following Figure 30).

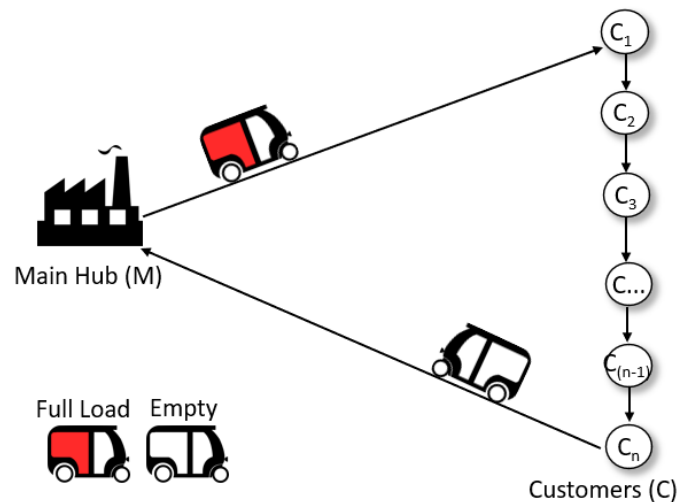


Figure 30: Process delivery and total distance travelled by vehicle in Scenario 0.

2.2.2.3. Delivery from Main Hub to Local Hub (Scenario 1 & 2)

The batch of orders is delivered using a single type of vehicle, which is dispatched from the Main Hub. Before the vehicle is sent, the batch of orders is sorted by the Local Hub to which each order is assigned. During delivery, the vehicle follows a strategy of delivering to the closest Local Hub first, if it has an order for that Hub. The vehicle then continues to the next closest Local Hub until all orders in the batch have been delivered. Finally, once all deliveries have been made, the vehicle returns to the Main Hub.

2.2.2.4. Delivery from Local Hub to Customer (Scenario 1)

Upon arrival at the Local Hub, orders undergo a preparation phase where they are grouped into batches based on the capacity of the last-mile delivery vehicle. In Scenario 1, each Local Hub is equipped with a specific number of vehicles that make up its private fleet. Once a batch is complete and a vehicle is available, it is dispatched for delivery to the customer.

In our use case study, there are four Local Hubs, one Main Hub, and several customers. It uses separate vehicles for transportation in terms of logistics optimization and improvements. Tuk-Tuks are used for transportation between the main hub and local hubs, and motorbikes are used for transportation between local hubs and customers. The total distance is divided into two calculations: Main Hub to Local Hubs and Local Hubs to Customers. The total distance is associated with cost and emission measurements which will be described in the next section.

The total distance can be calculated as simple as follows. M is the Main Hub and L is the Local Hub and C is the Customer. So, C_1-C_n : Customers 1 to n ; and L_1-L_n : Local hubs 1 to n .

$$Distance_full (M \text{ and } L) = M_1L_1 + (L_1L_2) + (L_2L_3) + \dots + (L_{(n-1)}L_n)$$

$$Distance_empty (M \text{ and } L) = L_nM_1$$

$$Distance_full (L \text{ and } C) = L_1C_1 + (C_1C_2) + (C_2C_3) + \dots + (C_{(n-1)}C_n)$$

$$Distance_empty (L \text{ and } C) = C_nL_1$$

So, $Total \text{ distance} = Distance_full (M \text{ and } L) + Distance_empty (M \text{ and } L) + Distance_full (L \text{ and } C) + Distance_empty (L \text{ and } C)$.

where:

$Distance_full (M \text{ and } L)$ is the total distance travelled from the main hub to the local hubs while carrying the orders. $Distance_empty (M \text{ and } L)$ is the total distance travelled from the last Local Hub to the Main Hub without carrying any packages. $Distance_full (L \text{ and } C)$ is the total distance travelled from the Local Hubs to the Customers while carrying the packages. $Distance_empty (L \text{ and } C)$ is the total distance travelled from the last customer to the local hub without carrying any packages (empty motorbike and the delivery motorbikes are located at Local Hub).

The orders are assumed to transit through at least one Local Hub. Our model is simulated using a nearest algorithm to determine the nearest vehicle, Local Hub, and Customers for transportation. Additionally, the delivery personnel can only transport 2 to 4 Local Hubs (not n Local Hubs between the Main Hub and Local Hub) and 15 or 18 Customers (not n Customers) (See the following Figure 31).

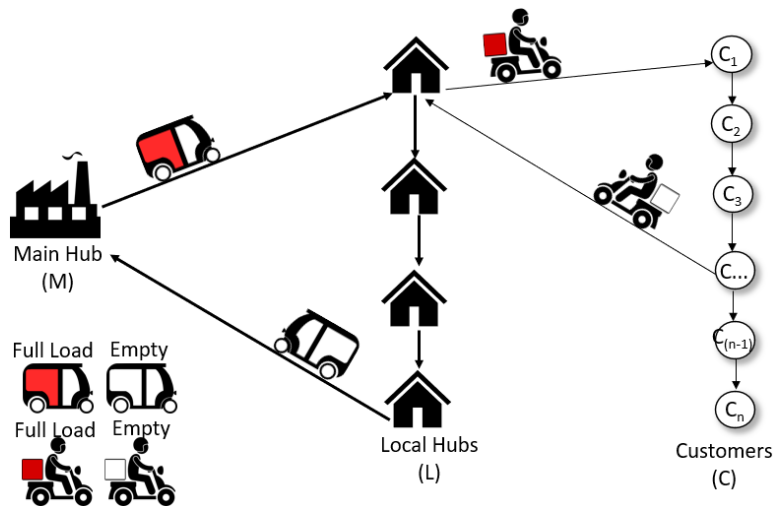


Figure 31: Process delivery and total distance travelled by vehicles in Scenario 1.

2.2.2.5. Delivery from Local Hub to Customer (Scenario 2)

Under scenario 2, when a batch is prepared and ready for delivery, a notification is sent to the nearest available on-demand vehicle. The vehicle then travels to the Local Hub to pick up the orders and delivers them to the closest customer, until all orders in the batch have been

delivered. Upon completion, the vehicle becomes available again and wanders randomly on the map, waiting for the next delivery request.

This Scenario is almost identical to Scenario 1, with the only difference being the inclusion of on-demand vehicles. The total distance calculation for these vehicles excludes the distance between the Local Hub and Customers, as it is not relevant to the overall distance traveled. However, the company will still be responsible for paying the service charge of these on-demand vehicles for customer fulfillment. After completing their delivery tasks, the on-demand vehicles will go elsewhere and continue on to their next destination. Therefore, our key performance indicators (KPIs) will take into account the service charge for on-demand vehicles, even though we do not have exact information on their location and destination beyond the delivery task.

The total distance is considered Main Hub and Local Hubs. Then the total distance would be the same as $Distance_full (M \text{ and } L) + Distance_empty (M \text{ and } L)$ from Scenario 1 (See the following Figure 32).

$$Distance_full (M \text{ and } L) = M_1L_1 + (L_1L_2) + (L_2L_3) + \dots + (L_{(n-1)}L_n)$$

$$Distance_empty (M \text{ and } L) = L_nM_1$$

So, the total distance would be:

$$Total \text{ Distance} = Distance_full (M \text{ and } L) + Distance_empty (M \text{ and } L)$$

In our simulation model, the on-demand package delivery queuing methodologies using ABM and DES modeling where the on-demand package delivery routing techniques are simulated including First-In-First-Out (FIFO) rule and Nearest algorithm.

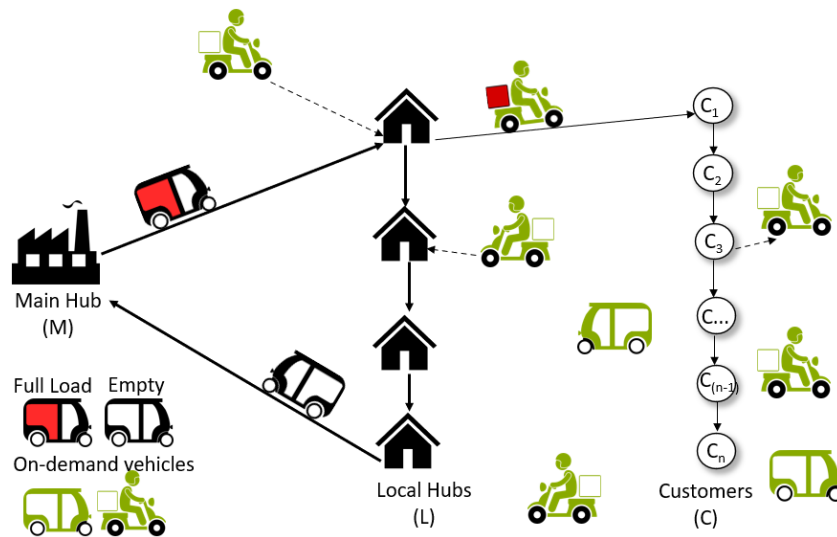


Figure 32: Process delivery and total distance travelled by vehicles in Scenario 2.

2.2.2.6. The batch rules

To prevent incomplete batches from waiting too long before being shipped, a rule has been established. If a batch remains incomplete for more than 30 minutes, it will be sent with the next available vehicle to ensure prompt delivery.

Typically, in this simulation, batches of orders are created for customer fulfillment. A 30-minute rule has been implemented where batches of orders are sent for delivery, even if they are not complete after 30 minutes. This means they will be sent with the first available vehicle. This rule has been put in place to optimize delivery times and minimize delays for customers. It is related to the order processing and delivery process. Additionally, the assumption of being "fully loaded" was made based on Physical Internet (PI) principles. These principles emphasize the importance of maximizing space utilization in logistics and transportation. As a result, the simulation assumes that there is no empty space in shipments. This assumption is related to the physical packing and utilization of space within the shipment.

It is important to note that batch orders of customer fulfillments and fully loaded shipments with no empty space are two different concepts. The 30-minute rule applies to the order processing and delivery process, while the assumption of being "fully loaded" is related to the physical packing and utilization of space within the shipment.

2.3. Environment of the agents

The main issue to consider regarding the environment of the simulation agents of the model is the traffic congestion. The previous chapters clearly stated that traffic congestion and accidents are major issues in developing countries. (Matsuoka, 2018) notes that the speed of vehicles is inversely proportional to their capacity, so motorbikes move faster than trucks or tuk-tuks. Basically, this feature is probably the most important one which has to be implemented in our model by considering different speeds depending on the location, the time and the type of vehicles, by adding variabilities and hazards in the traffic, and by including external vehicles in the model that might be considered as potentialities for the business of the company. The question is now how to define a realistic traffic pattern to be included in the model.

2.3.1. The data sources

Finding accessible data sets precisely describing the traffic of a city like Phnom Penh is not obvious. This information is mainly owned by GPS devices' companies or GAFA such as Google. To get them is quite expensive and we did not have such an opportunity. No open data seemed to be available. Alternatively, we found three interesting initiatives that we used for feeding our experiments:

- The Transport Expert Survey Team initiative (Transport Expert Survey Team, 2022) set up a database following a study which was conducted in 2022 in major zones and specific areas of Phnom Penh city, with a focus on the Central Business Districts (CBDs) and suburbs. Data collected was about the time of departure and arrival (start and end points of route), time of passing checkpoints, and time of stops/restarts along with the reason for stopping. The survey was carried out using the "floating car method" (the survey vehicle was required to maintain the same position in the traffic flow) and a Garmin GPSmap 62sc (GPS device) to track the drivers' travel information. For the ride-hailing services, the movements were recorded by a GPS device that encoded the travel log data, including coordinates (latitude, longitude) and time. The survey was conducted from 7:00 AM to 7:00 PM every day. Furthermore, the survey employed real

drivers who drove and worked as their usual working days in various city areas such as the market and city center.

- The reports from JICA and the Phnom Penh municipality established in the context of the project for a comprehensive urban transport plan in Phnom Penh capital city (JICA-PPUTMP, 2014). The design methodology of this initiative for collecting travel speed data included the survey of different types of vehicles, such as trucks (van or car types), and tuk-tuks in Phnom Penh city. The survey measured the speed of these vehicles as they travel along the major roads and almost specific areas at different times to provide a comprehensive understanding of the travel speeds in the city.
- Last but not least, as our study was connected to a real industrial case, we used it for gathering some data about the speed of vehicles in the context of the Phnom Penh city traffic conditions (see below).

2.3.2. The method

To integrate such traffic conditions into a model such as ours, two main alternatives are available. Firstly, it is possible to consider simulating all the vehicles circulating in the city according to operating patterns specific to schedules, location and vehicle types in particular. This option, which a priori allows us to propose a very fine and precise modelling of behaviors, seemed unreasonable in terms of implementation time, number of replications and computation time in the context of this research work and the associated objectives (Baldi et al., 2019; Chong & Osorio, 2018). We thus preferred to opt for a second, more accessible path, which aimed at identifying and characterizing average traffic behaviors in the city of Phnom Penh with a view to applying them to our vehicle agents. This method, already used in (Taniguchi & Heijden, 2010), seemed to us more appropriate in the context of this study. As traffic patterns and congestion in developing countries are often unpredictable and can be influenced by various factors, including infrastructure, driver behavior, and road conditions, this approach seemed sufficient to us.

2.3.3. City traffic patterns

Based on the three data sources previously mentioned, we noticed several key features:

- The mean speed tends to slow down not only during peak hours but throughout the whole day. This indicates that traffic congestion is a persistent problem in the city, with traffic jams occurring almost at any time.
- Each area of a city has a unique traffic pattern, especially during peak hours, which affects the speed of vehicles.
- As shown on the following Figure 33, during the day, motorcycles are faster than tuk-tuks and cars / vans in navigating through city traffic. Additionally, the average speed of motorcycles appears to be almost unaffected by traffic jam and quite constant during the day.

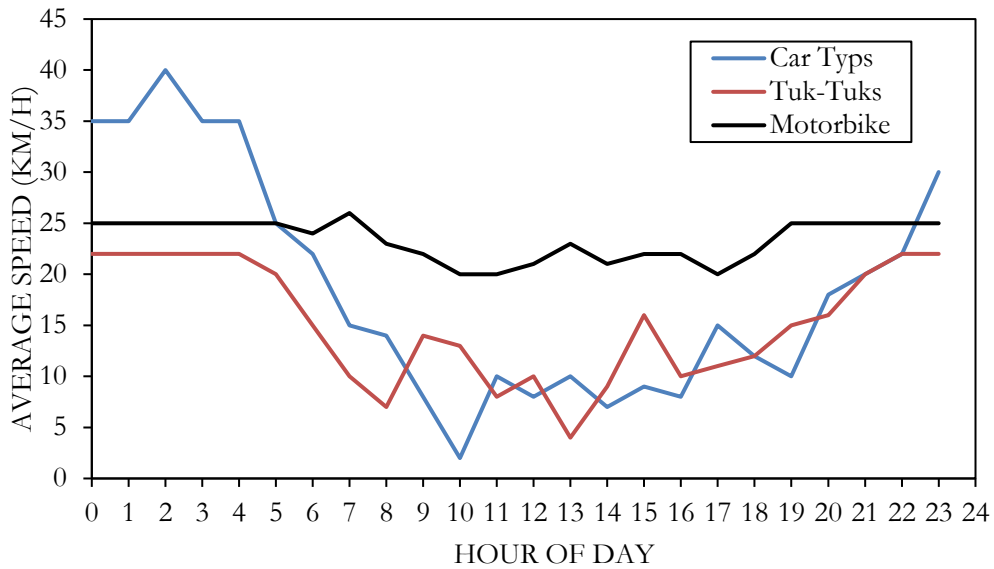


Figure 33: The mean speed of vehicles in Phnom Penh city depends on the hour of the day.

Based on those remarks, to model this traffic congestion pattern, an average travel speed has been assigned for each hour of the day and for each road type in the city as suggested by (Kim et al., 2021). Therefore, as suggested by (Taniguchi & Heijden, 2010), we developed a central traffic module able to dynamically set the average travel speeds based on the type of vehicles, the location, the day of the week and the time. Since the travel speeds are set dynamically, the model can be adjusted in response to changing traffic conditions in real-time. As a result, we were able to model traffic patterns in a way that is both accurate and efficient.

The detailed traffic pattern used is described in the following Table 7.

Table 7: Data of different vehicle types (cars, tuk-tuk, and motorcycle) used for the traffic pattern of Phnom Penh city

| Hour of Day | Car Types (km/h) | Tuk-Tuks (km/h) | Motorbike (km/h) |
|-------------|------------------|-----------------|------------------|
| 0 | 35 | 22 | 25 |
| 1 | 35 | 22 | 25 |
| 2 | 40 | 22 | 25 |
| 3 | 35 | 22 | 25 |
| 4 | 35 | 22 | 25 |
| 5 | 25 | 20 | 25 |
| 6 | 22 | 15 | 24 |
| 7 | 15 | 10 | 26 |
| 8 | 14 | 7 | 23 |
| 9 | 8 | 14 | 22 |
| 10 | 2 | 13 | 20 |
| 11 | 10 | 8 | 20 |
| 12 | 8 | 10 | 21 |
| 13 | 10 | 4 | 23 |
| 14 | 7 | 9 | 21 |

| | | | |
|----|----|----|----|
| 15 | 9 | 16 | 22 |
| 16 | 8 | 10 | 22 |
| 17 | 15 | 11 | 20 |
| 18 | 12 | 12 | 22 |
| 19 | 10 | 15 | 25 |
| 20 | 18 | 16 | 25 |
| 21 | 20 | 20 | 25 |
| 22 | 22 | 22 | 25 |
| 23 | 30 | 22 | 25 |

2.4. Business assumptions

The company operates and processes orders on a First-In, First-Out (FIFO) basis during the center's operating hours (7:00 am to 8:00 pm). The study assumes unlimited storage capacity and constant order preparation times, and only considers variability related to transport vehicle availability and vehicle speed related to traffic jam. The transport aspect of the model involves the use of the company's own vehicles, primarily motorcycles, to ensure delivery throughout the day, depending on the capacity of the chosen vehicle type (motorcycle, van, tuk-tuk, etc.) and a prearranged schedule. The vehicle routing is based on the shortest path algorithm and takes into account the inherent speed characteristics of the vehicle, as well as the traffic conditions of the relevant area, including congestion issues.

Regarding the processes of customer order fulfillment, each order represents a single parcel to be delivered to one customer at a particular postal address. For a specific day and time period, the average speed by vehicle category is consistent throughout the city.

Delivery vehicles have a fixed maximum capacity for parcels and can only make a limited number of stops per trip. Delivery vehicles have a set number of available drivers, and drivers have a maximum number of hours they can work per day.

Customers may be willing to pick up their parcels at a designated pickup location to save on delivery costs. That means some customers may prefer to collect their parcels at a designated pickup location, rather than having them delivered to their home or office, as this can help them save on delivery costs. Parcels are considered to be small and identical based on the information provided by the company.

All customers are present at home or at the locations where they place orders, so there is no package return or missed or failed delivery.

It is important to note that certain factors were not considered in the key assumptions for the simulation. For instance, customer preferences for faster delivery times, which may affect the delivery fees, and some delivery vehicles may experience downtime due to maintenance or repair, which may cause delays in the delivery schedule. In addition, traffic conditions or road closures may impact delivery times, and customers may have the option to select a preferred delivery window. Certain delivery areas may be classified as high-risk, and special safety measures may need to be taken to protect both the delivery driver and parcel. Finally, the e-commerce company may have partnerships with local businesses to act as pickup or delivery points for parcels, which may affect the delivery process.

3. Experimental features

3.1. Technical features

The AnyLogic modelling software, a Java-based simulation development platform that supports ABM and DES modelling methods, has been used to implement our multi-method simulation model developed for the PI-oriented city logistics of Phnom Penh city of Cambodia. The integration of Java-language architecture and GIS maps in the software facilitated the identification of breakthroughs related to complex city logistics systems.

The simulation was performed on a computer with an Intel(R) Core(TM) i7-10850H CPU @ 2.70GHz and 32GB of RAM. By utilizing this powerful hardware and software, the simulation was able to accurately model and analyze the PI-oriented city logistics of Phnom Penh, Cambodia. The high-performance hardware ensured that the simulation could be run efficiently and effectively, enabling the research work to obtain accurate and reliable results.

3.2. Performance assessment features

Key Performance Indicator used to assess the simulation results of the simulation are analyzed using Key Performance Indicators (KPIs) to assess the effectiveness of the PI paradigm and the different scenarios. Lead Time is used to measure the transportation time, excluding the preparation time. The Lead Time KPI is used to evaluate the time dimension of the PI paradigm and the delivery of goods in the last-mile (See Equation 1). LeadTime provides a clear measurement of the time taken from the preparation of goods at the Main Hub to their final delivery at the customer's location, and helps to assess the effectiveness of the delivery process.

$$LeadTime = TimeOrderDelivered - TimeOrderPlaced \quad (1)$$

The cost function KPI is used to assess the financial aspects of the PI paradigm. It provides a measure of the costs incurred in delivering goods from the main warehouse to the customer's location. It takes into account the type of vehicles used, the distance traveled, the fuel consumption, the spare parts replacements and the oil to calculate the overall cost of delivery. This KPI is important for evaluating the efficiency of the PI paradigm in a developing country context. The cost function for Scenario 0 and 1 is the same with the price being calculated based on a combination of a fixed initial fee per day and a mileage fare (see Equation 2). But slightly different for Scenario 2 due to the use of an on-demand vehicle service, we consider a fixed fare for order pickup cost of 5\$ per pickup. The different values used to build the cost function can be found in the following Table 8.

$$Cost = \sum_{n \text{ vehicles}} CostPerDay * NbDay + \frac{TotalDistance * VOC}{1000} \quad (2)$$

Additionally, a carbon footprint function is calculated to assess sustainability, which takes into account the type of vehicle used and the mileage traveled by each vehicle. The carbon footprint function KPI is used to assess the sustainability of the PI paradigm. It calculates the amount of carbon dioxide emissions produced during the delivery of goods from the main warehouse to the customer's location (see Equation 3). This KPI is important for evaluating the environmental impact of the PI paradigm and its alignment with sustainable development goals.

$$CarbonFootPrint = \sum_{n \text{ vehicles}} f(TotalDistance, Consumption, Type) \quad (3)$$

In conclusion, these three KPIs provide a comprehensive evaluation of the PI paradigm in terms of effectiveness, efficiency and sustainability, which are key aspects of the last mile delivery performance in a developing country context.

Table 8: Data used for KPI calculations

| Vehicle Specifications | Motorbike | Tuk-Tuk |
|---|----------------|---------|
| Purchase Cost (\$) | 3000 | 6000 |
| Life Time (year) | 5 | 5 |
| Cost per day Depreciation (\$/day) | 2 | 4 |
| Vehicle Operating Cost (VOC) (\$/1000km) (Maintenance) | 76,4 | 131,6 |
| Consumption (L/100km) | 1,84 | 5,2 |
| On-Demand fare | 5\$ per course | - |

Carbon FootPrint function: The order we consider are quite “small”, so we are not considering the weight of the orders to calculate the carbon footprint. So, for each vehicle we’ll calculate a “carbon footprint score” based on the distance traveled and their fuel consumption.

Table 9: Average CO2 emission factors (Hill et al., 2020; Reynolds et al., 2011)

| Vehicle type | Av. gCO ₂ e/km |
|-------------------------------|---------------------------|
| Cars and Vans | 151.8 |
| Medium motorbikes (125-300cc) | 93.1 |
| Autorickshaw (2 and 4-Stroke) | 98 ± 68 to 118 ± 47 |

3.3. Industrial case features

The case study of this research is about an e-commerce company called Little Fashion (mainly focused on fashion items), located in Phnom Penh city, typical of a developing country import business. Their consumers use a dedicated website (L192 App or www.l192.com) to order and are supposed to be delivered within one day at a maximum if the product is in stock, and within few days or weeks if the product is out-stock. The turnover of the company is growing very fast (also typical from a developing country) and according to the CEO, the main challenge of such a company is to manage properly the logistics issues, and particularly the last-mile deliveries. He said that it is very hard to reach the target of logistics services such as same day delivery guarantees, hassle-free delivery and the right products at the right time at the right place and in the exact amount.

The company has over 500,000 users and manages several thousands of items, both in-stock and out-stock, and its main suppliers are located in China, Thailand and Viet Nam. The company operates through one main warehouse and a small outlying one (not considered in this research work), both located in the city center and ownership of the company. The last-mile delivery is managed through a dedicated fleet (ownership of the company) of vehicles use through basic routings. Although, the company is thinking about a potential evolution of its network, its current supply chain is outlined as described in Scenario #0 (baseline). If the main

activity concerns the management of its own products, the company also offers logistics services to some other companies (particularly regarding transportation). However, this last point is not in the scope of the study. We must notice that the IT systems use for managing the information and material flows is quite mature, and a bar-code tracking system is running at each step of the process.

Little Fashion has a strong wish to reach a target same day delivery with less than or maximum 3 hours in the capital city. Additionally, warehouses are required a plenty of space for products and materials while these rental places in the capital city are expensive.

The logistic service charge is 0.5\$ for any delivery in the city.

In practice, Little Fashion company has 57 drivers, and each has their own motorbike for delivery. There are 15 three-wheelers. The three-wheelers are only used for transit items from one hub to one hub (transport goods between hubs). So, the quantity of motorbikes is 57 (consider to be a total number) and the quantity of three-wheelers is 15 for computational experiments. Three-wheeler delivery is referred to "Tuk-Tuk delivery" or "Autorickshaw delivery". This type of Autorickshaw delivery use gas (See Figure 34).



Figure 34: Little Fashion company's vehicles.

Most of parcels are small. Mostly the goods managed by the company are clothes, accessories, shampoos, shoes, bathroom stuff, cosmetics, etc. as described on the following Figure 35. Therefore, for this company, the average capacity of a motorbike is 18 parcels and the capacity of three-wheeler autorickshaw delivery is around 50 parcels.



Figure 35: Main business partnerships with Little Fashion.

The main warehouse (Main Hub) of this e-commerce company is typically a converted residential building located in the city. This warehouses usually have about three to four floors, each with a bulk storage area for products. To retrieve products from the upper floors (from ground floor to upper floor and vice versa), a traditional goods lift or freight elevator is used. This machine is designed to move products only, not people, and is not a modern lift (e.g., standard of smart warehouse) (see the Figure 36 below).



Figure 36: Main Hub/Warehouse operation at Boeung Keng Kang headquarters of Little Fashion, Phnom Penh, Cambodia.

At the ground floor, there is a fulfillment team who are working on sorting, consolidating, checking, picking, and packing, the products. When products are ready to deliver to the customer, it may wait for a specific time to deliver based on the customer's availability at home, so the product is stored in a nearby location "Holding area" or a "temporary storage area". These

products are not waiting too long; it is about 1 or 2 days maximum, but they have to deliver as soon as possible within a day oftentimes (same day delivery). Finally, the products will pass to the delivery team soon or later who are standby at the warehouse to dispatch to customers at home.

4. Results and discussions

4.1. Results of experiments

The experiment has been based on a one-week experiment considering customer orders between 02-08-2021 and 10-08-2021. This corresponds to 9100 orders placed by 8290 different customers. The type of vehicles and their specificities are detailed in the Table 10 below.

Table 10: Setup parameters of vehicles in each scenario

| | Scenario 0 | Scenario 1 | Scenario 2 |
|--------------------------|-------------------|-------------------|-------------------|
| Vehicle Main to Customer | Motorbike | - | - |
| Vehicle Main to Hub | - | Tuk-Tuk | Tuk-Tuk |
| Vehicle Hub to Customer | - | Motorbike | Motorbike |
| Nb of Motorbike | 57 | 57 | 100 |
| Capacity of Motorbike | 18 | 18 | 18 |
| Nb of Tuk-Tuk | - | 15 | 15 |
| Capacity of Tuk-Tuk | - | 50 | 50 |

Based on this simulation, we obtained the following results. According to the KPIs defined previously, we present here successively the results on lead times, carbon footprint and costs.

Table 11: Descriptive Statistics (in hour) on Lead Time for Each Scenario.

| LEAD TIME STATS (hours) | S0 | S1 | S2 |
|------------------------------------|-----------|-----------|-----------|
| STD Dev | 4.842 | 4.457 | 4.367 |
| Min | 0.190 | 1.166 | 1.176 |
| Median | 8.190 | 5.109 | 3.725 |
| Mean | 8.365 | 6.610 | 5.610 |
| Max | 25.470 | 20.375 | 18.989 |

Table 12: Comparison lead time for each scenario

| COMPARISON - % | S1/S0 | S2/S0 | S2/S1 |
|-----------------------|--------------|--------------|--------------|
| STD Dev | -8% | -10% | -2% |
| Median | -38% | -55% | -27% |
| Mean | -21% | -33% | -15% |
| Min | 514% | 519% | 1% |
| Max | -20% | -25% | -7% |

Regarding the lead times, the results in Table 11 and 12 show that there are clear benefits to using scenario 1 compared to scenario 0 and scenario 2 compared to scenario 1. The median and mean lead times in scenario 2 are shorter than those of scenario 1 and 0. Furthermore, the lower mean in scenarios 1 and 2 is followed by a reduced standard deviation, which indicates the overall benefit of these scenarios compared to scenario 0. Therefore, scenario 2 is the best practice based on the results of the standard deviation, median, and mean.

Mean of lead time in scenario 2 is 5,61 hours which is better than 8,365 in scenario 0. This is a reduction of mean lead time by almost 33%. Median of lead time in scenario 2 is 3,725 hours which is better than 8,190 in scenario 0. This is a reduction of median lead time by 55%. Standard deviation of lead time in scenario 2 is 4,367 hours which is better than 4,842 in scenario 0. This is a reduction of standard deviation of lead time by 10%.

Minimum of lead time in scenario 2 is 1,176 hours which is not better than 0,190 in scenario 0. This can be balanced by the average and median that are globally better in scenario 2. However, Maximum of lead time in scenario 2 is 18,989 hours which is shorter than 25,470 in scenario 0. This is a reduction of maximum lead time by 25%.

Lead time is an essential factor in customer satisfaction, and it can have a significant impact on business success. According to the lead time distribution of Scenario 0, depicted in Figure 37, processing around 92% of customer orders takes approximately 14.28 hours of lead times, while processing around 8% of customer orders takes about 11.76 hours of lead times. Overall, the baseline takes approximately 25.47 hours of max lead time to process all customer orders. In Scenario 1, shown in Figure 38, the max lead time is about 20.38 hours, which is approximately 5.1 hours or 20% less than the baseline. In Scenario 2, as shown in Figure 39, the max lead time for fulfilling all customer orders is around 19 hours, which can be reduced by approximately 6.5 hours or 25% compared to the baseline. General, the results suggest that implementing Scenarios 1 or 2 could significantly improve the lead time for fulfilling customer orders compared to the baseline Scenario 0.

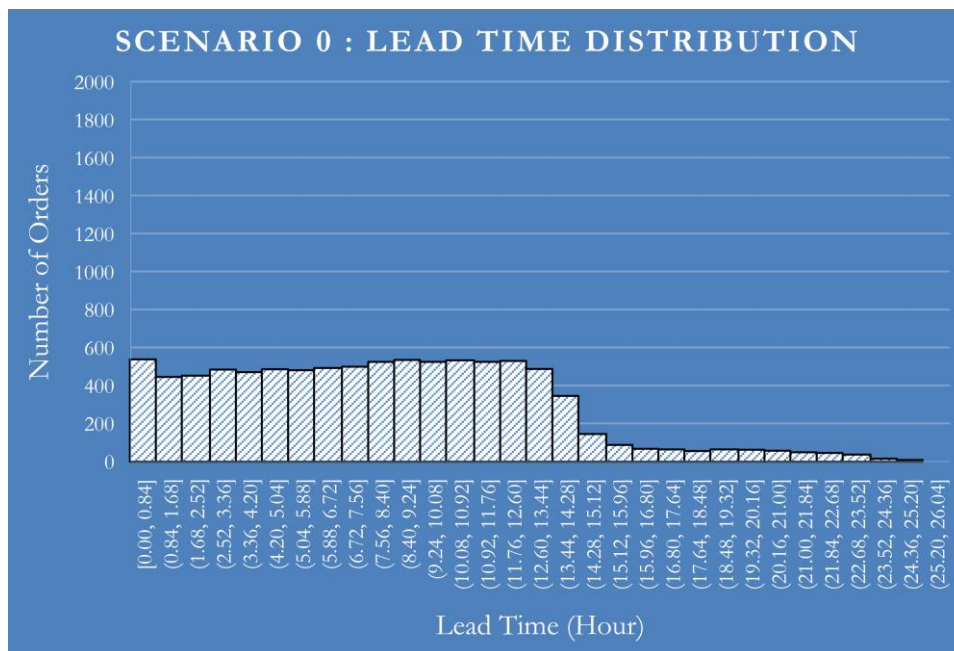


Figure 37: Lead time distribution in Scenario 0.

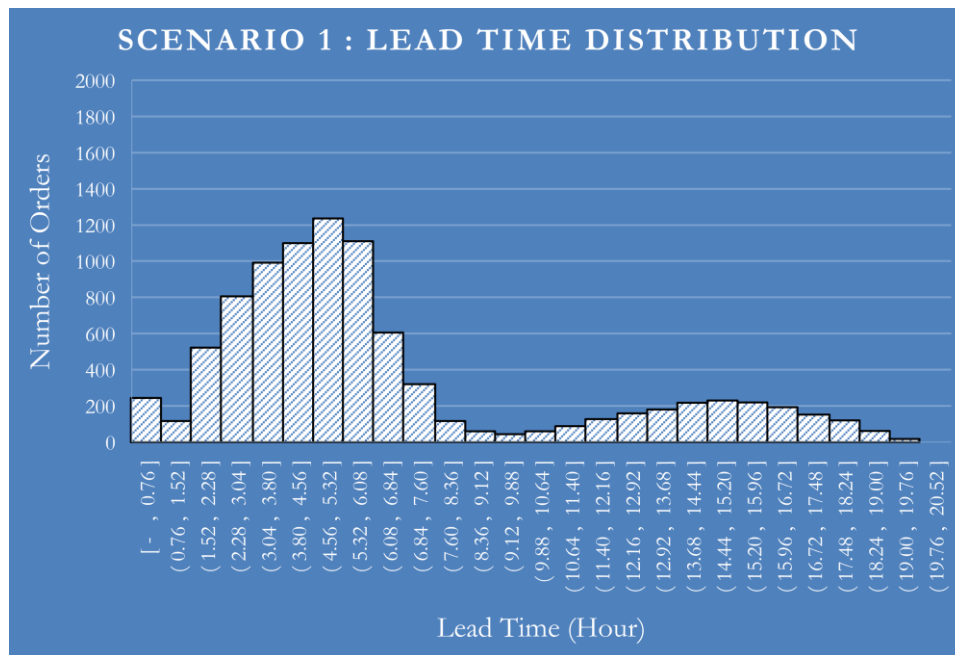


Figure 38: Lead time distribution of Scenario 1

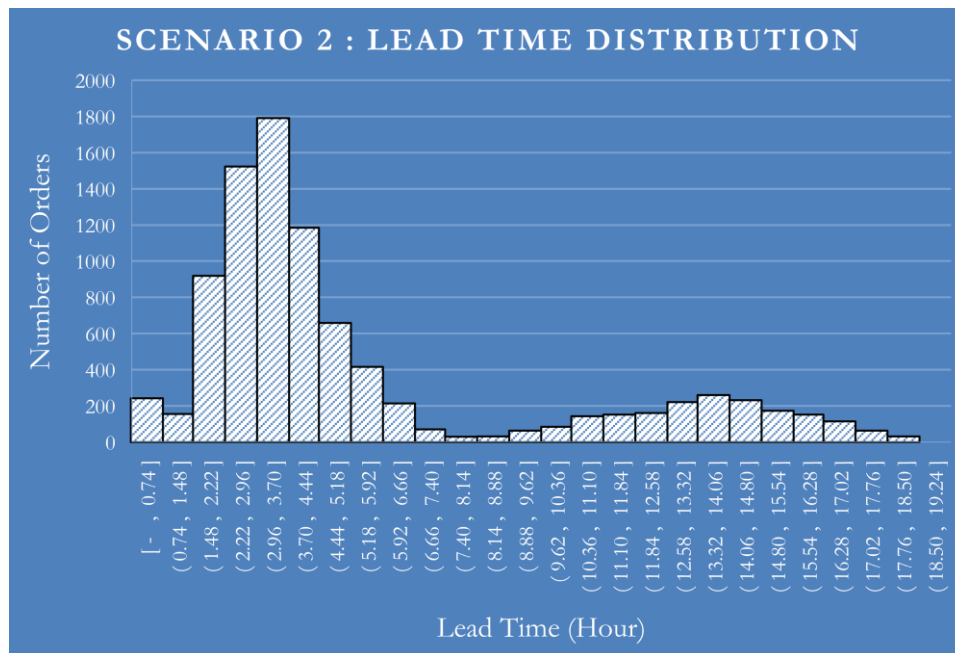


Figure 39: Lead time distribution of Scenario 2

Now, let's have a look on the carbon footprint emissions of each scenario in the following Table 13.

Table 13: Carbon Footprint for each scenario

| | Carbon Foot Print | | | Comparison to Scenario 0 (%) |
|-------------------|-------------------|-----------------|---------------------------------|------------------------------|
| | Main to Hub | Hub to Customer | Total (ton of CO ₂) | |
| Scenario 0 | | 17.8 | 17.8 | - |
| Scenario 1 | 0.602 | 6.5 | 7.10 | 60% |
| Scenario 2 | 0.602 | 6.3 | 6.90 | 61% |

Based on the comparison of carbon footprint for the three scenarios, it can be observed that scenario 1 and scenario 2 have significant carbon emission savings as compared to scenario 0. Scenario 1 estimates a carbon footprint of 7.10 tons of CO₂, which is a 60% reduction in emissions compared to scenario 0. On the other hand, scenario 2 estimates a carbon footprint of 6.90 tons of CO₂, which is a 61% reduction in emissions compared to scenario 0. This indicates that implementing either scenario 1 or 2 can result in a significant reduction in carbon emissions, with scenario 2 showing slightly better results (See Figure 40). It is important to note that reducing carbon emissions not only benefits the environment but also positively impacts a company's reputation and sustainability efforts.

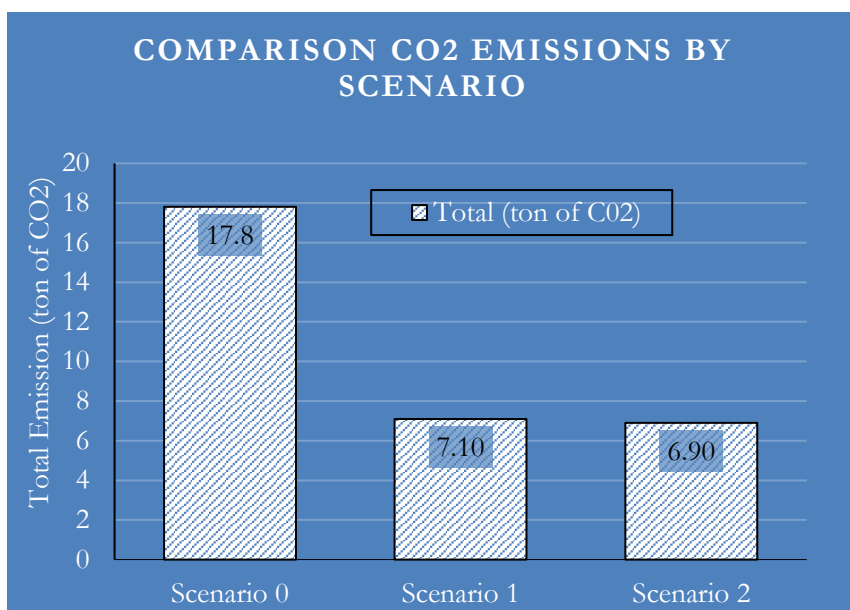


Figure 40: Carbon emissions for each scenario

Last, the results in matter of operating costs were the following Table 14 for each scenario.

Table 14: Vehicle Operating Cost for each Scenario

| | Vehicle Operating Cost (\$) | | | Comparison to Scenario 0 (%) |
|-------------------|-----------------------------|-----------------|------------|------------------------------|
| | Main to Hub | Hub to Customer | Total (\$) | |
| Scenario 0 | 10,000 | | 10,000 | - |
| Scenario 1 | 382 | 6604 | 6,986 | 30% |
| Scenario 2 | 245 | 2460 | 2,705 | 73% |

To help us analysing the results, the costs have been normalized in reference to the baseline (Scenario 0). Then, the vehicle operating cost of scenario was \$10,000. Then, the analysis of costs for the three scenarios reveals that scenario 1 is 30% less expensive than scenario 0, with a total cost of \$6,986. Meanwhile, scenario 2 is around 73% less expensive than scenario 0, with a total cost of \$2,705. These results demonstrate the potential cost savings associated with the implementation of a local hub and on-demand fleets. By introducing this new approach, the overall costs associated with last-mile delivery operations can be significantly reduced. As such,

it can be concluded that scenario 1 and 2 are more cost-effective alternatives to the baseline scenario 0 (see Figure 41).

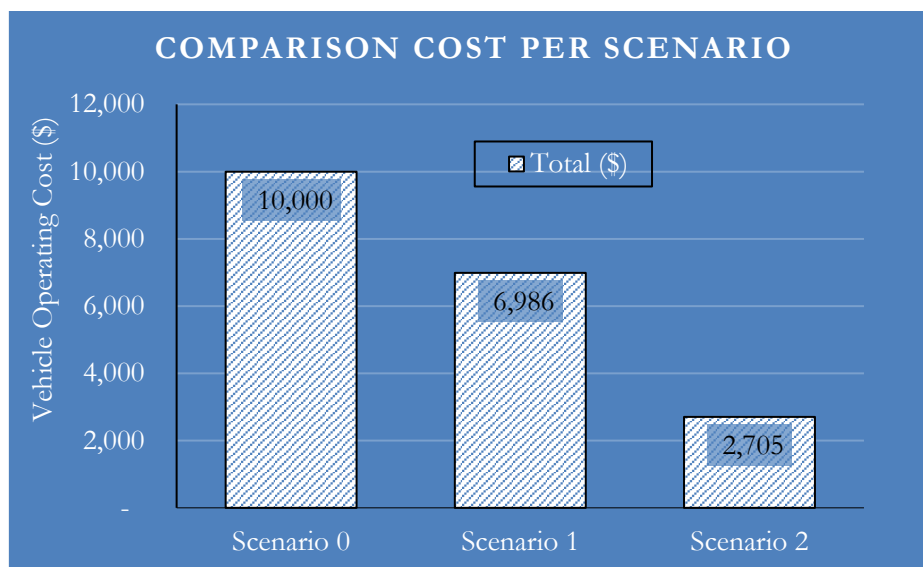


Figure 41: Cost comparison of fleet utilization for each scenario

4.2. Discussion

In the three scenarios, we observe that we were able to deliver respectively 8742, 8854, and 8856 for scenarios 0, 1, and 2. It is important to note that there were 9100 orders placed during this week. So, with the use of PI scenarios, let us reduce the non-served order rate from 4% to 3%, so that there are 100 extra orders that can be delivered.

Considering the Lead Time, Table 11 and 12 summarizes the results obtained. The Median Lead Time is 8.19, 5.11, and 3.72 hours for scenario 0, 1 and 2, respectively. Adding Local Hub with motorbike fleets could improve the Lead Time by 37% as compared to the baseline scenario. Furthermore, using Local Hubs and on-demand fleets improve the median lead time by 54% and let us gain one additional hour on the delivery which is quite interesting for a Last-Mile Delivery on e-commerce. Meanwhile, the maximum lead time could seem quite high, however, it can be explained by the orders overlapping between two days and which are not delivered on the same day it is received. This maximum lead time has been reduced from 25 hours to 19 hours. It is an improvement of 24% compared to the baseline.

The Carbon Footprint for each Scenario is detailed in the Table 13. The Scenario 0 considers only Tuk-Tuks, Scenario 1 and 2 consider a mix of Tuk-Tuks and Motorbikes. The results show that the use of Tuk-Tuks as a mode of transportation results in a higher fuel consumption compared to motorcycles, leading to a higher carbon footprint in Scenario 0. However, by utilizing a hub system and utilizing lighter means of transportation such as motorcycles for last-mile delivery, the company was able to achieve a significant reduction in their carbon footprint. In fact, there was a 60% decrease in carbon emissions from the baseline, going from 17.8 tons of CO₂ produced per week to only 7 tons of CO₂ produced. The implementation of an on-demand vehicle system leads in a decrease in the total distance covered by the vehicles, leading to a slight reduction in the company's carbon footprint from 7.10 tons of CO₂ to 6.90.

However, this decrease should be considered with caution as the transportation still occurs and emissions are still produced, only the responsibility is transferred to the on-demand vehicles. Thus, it can be seen as a shift in responsibility rather than a genuine reduction of carbon emissions between Scenarios 1 and 2.

The Table 14 summarizes the cost of each scenario. The cost calculation takes into consideration factors such as depreciation, maintenance, and fuel expenses for the vehicles. For the on-demand fleet scenario, the cost is calculated based on a fixed initial fee and a mileage fee. The scenario with its own fleet of Tuk-Tuks (Scenario 0) incurs the highest weekly cost of \$10,000 (normalized reference). By switching to a fleet of motorcycles in Scenario 1, the cost is reduced by 30% to \$6,986. The implementation of an on-demand fleet (Scenario 2) results in an even greater reduction of 73% to \$2,705, with a fixed pickup cost of \$5.

Now we can answer to the previous research questions based on the results of this study:

RQ1: How can the principles of the PI be implemented in the context of city logistics in developing countries?

We have shown in Chapter III that PI concepts can be perfectly applied to the particular conditions of urban logistics in developing countries. In particular, we have proposed 3 simple implementation scenarios that build on existing logistics infrastructures and means. Other options are obviously possible but will probably require more investments. The experimentation conducted on the case of the distribution of products of an e-commerce company in the city of Phnom Penh confirms the feasibility of implementation.

RQ2: How can the application of PI concepts to city logistics of developing countries be assessed in terms of its impact on performance?

The application of PI concepts to city logistics of developing countries can be assessed in terms of its impact on performance by measuring key performance indicators (KPIs) such as lead time, logistics costs, and carbon emissions. Although very standard, these indicators make it possible to objectify the scope of the proposed scenarios for manufacturers, logisticians and the socio-economic environment in which the solutions will be implemented.

RQ3: What are the concrete benefits that can be expected from the implementation of the PI on the case of city logistics in developing countries?

Through the development of a hybrid simulation model, we were able to test the scope of our proposed scenarios #1 and #2. The results show a very significant impact on the economy (cost), the environment (carbon footprint) and customer service quality (cycle time). The results of our study show that scenario 2, which incorporates both local hubs and on-demand fleets, provides the greatest benefits in terms of all three KPIs. Although conceptualized and partially modeled, scenario #3 could not be implemented due to lack of available data. We are not able to quantitatively conclude regarding this specific scenario.

4.3. Study Limitations

The limitations of the simulation study of PI-oriented city logistics are also important to discuss. Firstly, the example used in the simulation is limited to one week of real data for customer order fulfilment. This may not provide an accurate representation of long-term trends or variations in demand for freight transport.

Secondly, assumptions were made about traffic, which may not totally reflect the real-world variations in traffic patterns. The scenarios used in the simulation are deterministic, and there is no consideration of stochastic scenarios that may arise.

Thirdly, the model relies on approximates for several data and parameters. Without a sensitivity analysis (which we did not have time to perform in the time available for this thesis), it is difficult to determine the impact of these approximations on the simulation results.

Fourthly, the simulation only considers a specific geographic area and may not be applicable to other cities or regions with different characteristics. There is no replication in the simulation to account for variations in different regions.

Fifthly, the simulation does not account for external factors that may affect city logistics, such as changes in government policies, natural disasters, or economic downturns. These factors may significantly impact the performance of the logistics system. Also, the simulation does not consider the impact of unexpected events or disruptions on the performance of the logistics system. It assumes that all actors in the logistics system behave rationally and make optimal decisions, which may not be the case in reality.

Finally, the simulation does not include any environmental or social indicators other than carbon emissions, such as noise pollution or air quality. It is essential to note that noise pollution and air quality can also have significant impacts on human health and well-being.

CHAPTER V. CONCLUSION

“If you double the number of experiments you do per year you're going to double your inventiveness.”

~ *Jeff Bezos, founder of Amazon, Wired magazine, 2011*

This chapter concludes this document by proposing a quick synthesis of the problems addressed and the associated contributions, and by opening an important field of research perspectives for the short, medium and long term.

Research summary and thesis contributions

In Chapter 1, the research study focuses on the context and problem statements of developing countries, particularly in Southeast Asia, with a specific emphasis on city logistics. The chapter provided a detailed understanding of the critical characteristics of developing countries, such as revenue, business, social, and land development challenges, and how these challenges lead to city logistics problems. Furthermore, the city logistics (e.g., last-mile delivery) challenges were also highlighted, including traffic congestion, unsafe roads, few and poor-quality infrastructures, expensive and unreliable vehicles, and a high growth rate of population, urbanization, and etc. Therefore, developing countries face various challenges such as low income, dependence on specific sectors, low productivity, limited opportunities for employment, poor health and education, corruption, and specific city logistics issues. Hence, they have difficulty managing their city logistics activities sustainably and supporting their economy. While investing in new infrastructure and transportation means is necessary, it can take decades to bring about tangible results. The chapter also suggested that it could be a solution to use existing assets and resources, but differently. With such an ambition, the Physical Internet (PI) has been identified as a potentially relevant candidate for enhancing developing countries' city logistics activities.

To investigate this potential, Chapter 2 proposed a state of the art on PI research works divided into six main categories: PI-concepts, PI-assessments, PI-components, innovative facilities used in the PI, collaboration in the PI, and PI implementations. A specific focus on how the PI could be considered in the context of developing countries was proposed. Based on this extensive material, the three following research questions were formulated:

- RQ1: How can the principles of the PI be implemented in the context of city logistics in developing countries?
- RQ2: How can the application of PI concepts to city logistics of developing countries be assessed in terms of its impact on performance?
- RQ3: What are the concrete benefits that can be expected from the implementation of the PI on the case of city logistics in developing countries?

To solve those questions, we proposed a design science research methodology consisting of four main phases and nine steps.

Inspired by (Crainic & Montreuil, 2016), the Chapter 3 developed a conceptual contribution in regards of the first research question. The chapter assessed the accessibility and stake levels of each PI concepts previously described and concluded that the priority ones for solving our problem statement should be “Information sharing and standardized systems”, “Collaborative multifaceted activities”, and “Open system stakeholder interconnections”. Based on this, a set of scenarios were designed allowing to put PI into practice for better delivering goods in the context of city logistics in developing countries. These scenarios were organized through the implementation of PI-hubs, on-demand and as-a-service transportation systems, and sharing of assets.

Chapter 4 developed the technical and experimental contributions of the research work. These contributions were developed in regards of RQ2 and RQ3. The first contribution consists in setting a dedicated hybrid simulation model based on agent-based modeling (ABM) and discrete event simulation (DES). The chapter provides details on the technical model implemented,

including data, parameters, variables, and assumptions. It also includes the definition of specific performance indicators able to measure the potential impacts of the scenarios design in Chapter 3 regarding the baseline scenario (lead time, logistics costs, and carbon footprint). The experimental contribution is developed on a basis of a real industrial case, related to e-commerce logistics activities in Phnom Penh city (Cambodia). It includes a set of solutions for modelling traffic patterns using real survey data of different types of vehicles traveled in the city. Last but not least, numerical results are presented showing the clear benefit of using PI-hubs and especially on-demand and as-a-service transportation systems. The gains concern all the dimensions of performance, and allow very substantial savings: up to 55% for lead times, 61% for carbon foot print and 75% for logistics costs. These results obviously tend to confirm the initial research hypothesis that the use of certain PI concepts could drastically improve the performance of urban logistics activities, and this without any particularly large investment. However, the study has some important limitations, which are discussed in Chapter 4. These elements naturally lead us to consider a large number of perspectives that we discuss in the following.

Future works and perspectives

The perspectives associated with this research work are obviously very numerous. We will distinguish between industrial and research perspectives.

Regarding the former, and even if we are already able to affirm the benefits of the PI on urban logistics in developing countries, it would seem appropriate to consider the following actions in order to consolidate its operational recommendations that we could make:

- To develop the application case by extending the time period considered (1 week currently) and making sensitivity analyses on all the parameters and data of the model. This is a critical next step to allow verifying and validating the robustness of the results and associated recommendations for practitioners.
- To strengthen the validation work of the use case data by working more closely with practitioners, notably on the relevance of the assumptions made and data used. Here also, this step is important to ensure the validity of the conclusions of the research.
- To extend the proposed simulations to other industrial cases, in particular to businesses that do not come from e-commerce. As e-commerce gets some specificities, it would be interesting to consider other categories of businesses which can have different features, need different type of solutions in matter of implementation and get different kind of results.
- To continue the experiments to other urban logistics environments (cities in other countries for example). Most of the data and parameters used in this research work has been extracted from the field and consequently are very Phnom Penh oriented. It would be good to ensure that the work remains consistent in other developing countries beyond this particular city.
- To develop a new experimental case that will allow to test the proposed scenario #3 in order to evaluate the impact of the sharing of resources on the performance indicators. This one will need a minimum of two or more purchasers having same kind of customers located in a same city. This is a major perspective as the conceptual work made as shown the potentiality of this scenario but the time constraint for the execution of this thesis did not allow us verifying it through a concrete experiment.
- To consider concrete implementations in the field inspired by the simulations carried out in order to finish validating the business recommendations made. Particularly, a concrete implementation of the business recommendations developed in the study with the Little Fashion company, partner of this research work, seems to be a priority. We can imagine to see up few PI-Hubs in the following months in the city of Phnom Penh and also probably to test the on-demand transportation systems with few of them.
- To propose, with a medium-term perspective, a communication plan for companies and public institutions of developing countries likely to give a large-scale operational follow-up to this study. It will involve to analyze the social and economic implications of implementing the defined scenarios (particularly 1 and 2), such as their potential impact on employment, local businesses, and consumer behavior. This could help ensure that the proposed solutions are sustainable and equitable. Making the results of scientific research known to the socio-economic world is a challenge too often neglected.

Regarding the latter, the conditions under which this thesis was carried out did not allow us to fully explore all of the research hypotheses. In addition, the obtained results opened many avenues for further scientific research remains, notably:

- To investigate much more widely how to take into account the specificities of the logistics environment of last-mile transport in developing countries. For the moment, our approach is limited to a realistic but relatively simplistic one (adjusting vehicle speeds according to geographical and time constraints for example) that only partially takes into account the complexity of the existing factors. Other research works have made different choices to do such a thing. One can imagine, for instance, to simulate or emulate based on a digital twin solution all the vehicles of a given city based on GPS data available.
- To extend the scenario design to the other PI components that we highlighted in the study. Indeed, if our study has allowed us to model the most promising levers of PI and has already demonstrated very significant potential benefits, many other potential axes remain to be formalized and evaluated. Only 3 of the 9 dimensions of the framework we proposed could be exploited in this thesis work and generated 3 PI-oriented scenarios. The additional ones are thus possibly very numerous, allowing to consider gains and answers to the problems of urban logistics in developing countries even more important.
- To work on extending the proposed models and simulations in order to truly consider the potential for mutualization and sharing between companies. Unfortunately, if the ambition of the thesis was indeed to evaluate the potential of the Physical Internet, we have to admit that the results produced are limited to what we could call the Physical Intranet, at least for the shippers. There is clearly a lack of the guiding idea of the PI, which considers that shippers can and must share their resources and learn to mutualize their activities. This idea, although mentioned throughout the thesis, has not been sufficiently investigated.
- To work to optimize order response and processes in an PI context. To date, only very simple implementation rules have been tested to support the implementation of the research work (FIFO for order processing, shortest path for vehicle routes...). Many better alternatives could be imagined to further improve the effectiveness and efficiency of the scenarios. Scientific tools from the world of Optimization or Machine Learning could be mobilized to good effect. The perspectives on this point are numerous and very promising.
- To consider additional performance indicators for supporting the analysis of the results. Although we have tried to propose a robust performance analysis based on a sustainable development perspective, it is currently limited to three relatively simple indicators. Other performance dimensions could be considered to improve the quality of the evaluation of the advantages and disadvantages of the proposed solutions. In particular, indicators on the societal dimension would be welcome, and the part related to the measurement of the quality of service for customers could be strongly enriched. It should also be noted that the supply of these indicators requires access to basic data that must be consistent to guarantee the relevance of the results (cost per kilo/kilometer, for

example). These data are not always easily accessible and are especially volatile. Work could also be done to consolidate the quality of these data.

- To study the extension of the approach to the rest of the supply chains (supply, production, warehousing...) in order not to limit the potential use of the PI to the final deliveries. This is obvious but the logistics issues of developing countries are not limited to last-mile deliveries. If we made the choice to focus on this specific problem in the context of this study, the proposed approach could be opened to the rest of the supply chain without difficulty. Applications to inter-urban logistics, import-export logistics, or procurement are also very important issues in developing countries.

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APPENDICES

The results of each scenario simulation are presented in Table 1. The table includes various statistical measures such as standard deviation, minimum value, median, mean value, and maximum value. These measures provide a comprehensive overview of the simulation outcomes and offer valuable insights into the performance of each scenario.

Table1: Descriptive Statistics (in hour) on Lead Time for Each Scenario.

| Lead time stats (hours) | S0 | S1 | S2 |
|-------------------------|--------|--------|--------|
| STD Dev | 4.842 | 4.457 | 4.367 |
| Min | 0.190 | 1.166 | 1.176 |
| Median | 8.190 | 5.109 | 3.725 |
| Mean | 8.365 | 6.610 | 5.610 |
| Max | 25.470 | 20.375 | 18.989 |

Figure 1 below illustrates the comparison of mean lead time between scenarios. Scenario 1 demonstrates a reduction of approximately 1.75 hours or 21% in mean lead time compared to the baseline scenario 0. Similarly, Scenario 2 exhibits a reduction of around 2.76 hours or 33% in mean lead time compared to the baseline scenario 0. The figure provides a clear visualization of the significant improvements achieved in lead time through the implementation of these scenarios.

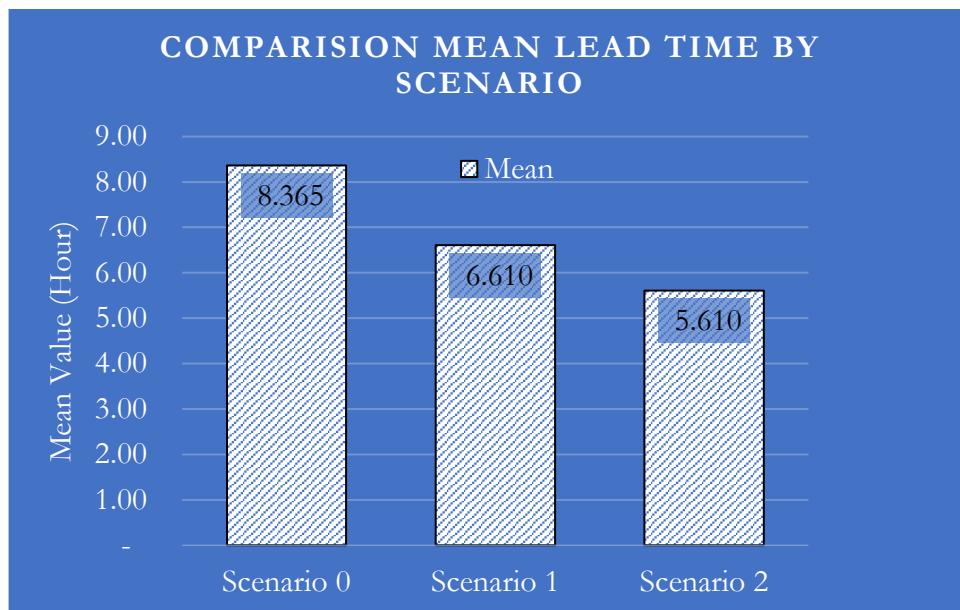


Figure 1: Mean value of lead time by scenario

Figure 2 below illustrates the comparison of maximum lead time between scenarios. In Scenario 1, the maximum lead time can be reduced by approximately 5.1 hours or 20% compared to the baseline scenario 0. Similarly, in Scenario 2, the maximum lead time can be reduced by around 6.5 hours or 25% compared to the baseline scenario 0. The figure provides a clear visual representation of the significant improvements achieved in terms of reducing the maximum lead time through the implementation of these scenarios.

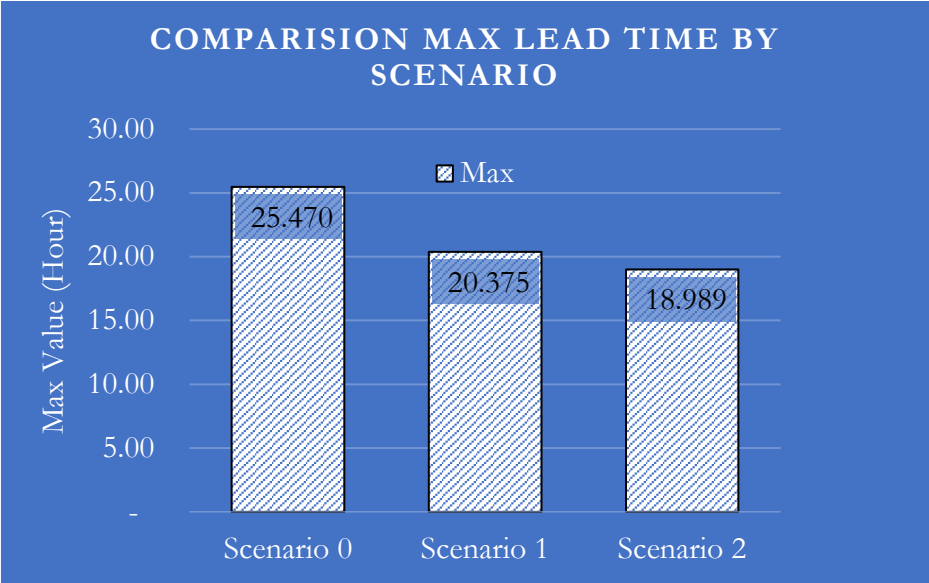


Figure 2: Max value of lead time by scenario

ÉVALUATION DU POTENTIEL DE L'INTERNET PHYSIQUE POUR LES ACTIVITÉS DE LOGISTIQUE URBAINE DANS LES PAYS EN DÉVELOPPEMENT

Résumé :

Le travail de recherche vise à relever les défis de la logistique urbaine auxquels sont confrontés les pays en développement, notamment en Asie du Sud-Est. Le chapitre 1 propose une étude des caractéristiques essentielles de ces pays, telles que les défis en matière de revenus, de société et de développement du territoire, et de la manière dont ces défis conduisent aux problèmes de logistique urbaine, notamment via les embouteillages, les routes non sécurisées, les infrastructures de mauvaise qualité, les véhicules chers et peu fiables, le taux de croissance démographique élevé et l'urbanisation. Les difficultés à gérer durablement leurs activités de logistique urbaine et à soutenir leur économie sont ainsi soulignées.

Le chapitre 2 donne un aperçu des travaux de recherche sur l'Internet physique (IP) et de la manière dont ils peuvent être envisagés dans le contexte des pays en développement. Les questions de recherche sont formulées sur la base de cette connaissance, à savoir comment les principes de l'IP peuvent être mis en œuvre dans le contexte de la logistique urbaine dans les pays en développement, comment l'application des concepts de l'IP peut être évaluée en termes d'impact sur les performances, et quels sont les avantages que l'on peut attendre de la mise en œuvre de l'IP dans le cas de la logistique urbaine dans les pays en développement. Pour résoudre ces questions, la thèse propose une méthodologie de recherche comprenant quatre phases principales et neuf étapes.

Le chapitre 3 élabore une contribution conceptuelle en évaluant l'accessibilité et les niveaux d'intérêt de chaque concept d'IP et conclut que les concepts prioritaires pour résoudre l'énoncé du problème devraient être le partage d'informations et les systèmes normalisés, les activités collaboratives et les interconnexions entre les parties prenantes. Sur cette base, un ensemble de scénarios a été conçu pour mettre en pratique l'IP afin de mieux livrer les marchandises dans le contexte de la logistique urbaine des pays en développement. Ces scénarios ont été organisés notamment à travers la mise en œuvre de PI-hubs, de systèmes de transport à la demande, et du partage des actifs.

Le chapitre 4 développe les contributions techniques et expérimentales du travail de recherche en établissant un modèle de simulation hybride dédié basé sur la modélisation à base d'agents et la simulation à événements discrets. Il comprend la définition d'indicateurs de performance spécifiques capables de mesurer les impacts potentiels des scénarios conçus au chapitre 3 par rapport au scénario de base. La contribution expérimentale est développée sur la base d'un cas industriel réel lié aux activités logistiques du commerce électronique dans la ville de Phnom Penh (Cambodge). Les résultats numériques montrent les avantages évidents de l'utilisation des PI-hubs et des systèmes de transport à la demande, qui permettent des économies très substantielles allant jusqu'à 55% pour la qualité de service, 61% pour les empreintes carbone et 75% pour les coûts logistiques. Cependant, l'étude présente certaines limites, qui sont également discutées.

Globalement, le travail de recherche conclut que l'utilisation de certains concepts d'IP pourrait améliorer considérablement les performances des activités de logistique urbaine dans les pays en développement, sans investissement particulièrement important. L'étude propose plusieurs perspectives de recherche futures, notamment l'utilisation de l'IP dans différents contextes et le développement d'outils d'aide à la décision opérationnels pour la mise en œuvre de l'IP dans la logistique urbaine de ces pays.

Mots clés : Internet Physique, Logistique urbaine, Simulation, Pays en développement, Logistique du dernier kilomètre, Cambodge.

ASSESSING THE POTENTIAL OF THE PHYSICAL INTERNET FOR CITY LOGISTICS ACTIVITIES IN DEVELOPING COUNTRIES

Abstract:

The research study aims to address the city logistics challenges faced by developing countries, notably in Southeast Asia. Chapter 1 provides a detailed understanding of the critical characteristics of developing countries, such as revenue, business, social, and land development challenges, and how these challenges lead to city logistics problems. These challenges include traffic congestion, unsafe roads, poor-quality infrastructures, expensive and unreliable vehicles, high population growth rate, and urbanization. Hence, they have difficulty managing their city logistics activities sustainably and supporting their economy.

Chapter 2 provides an overview of the Physical Internet (PI) research works and how it can be considered in the context of developing countries. The research questions are formulated based on this extensive material, which are how the principles of PI can be implemented in the context of city logistics in developing countries, how the application of PI concepts can be assessed in terms of its impact on performance, and what are the benefits that can be expected from the implementation of PI on the case of city logistics in developing countries. To solve these questions, the research proposes a design science research methodology consisting of four main phases and nine steps.

Chapter 3 developed a conceptual contribution by assessing the accessibility and stake levels of each PI concept and concluded that the priority ones for solving the problem statement should be information sharing and standardized systems, collaborative multifaceted activities, and open system stakeholder interconnections. A set of scenarios were designed to put PI into practice for better delivering goods in the context of city logistics in developing countries. These scenarios were organized through the implementation of PI-hubs, on-demand and as-a-service transportation systems, and sharing of assets.

Chapter 4 developed the technical and experimental contributions of the research work by setting a dedicated hybrid simulation model based on agent-based modeling and discrete event simulation. It includes the definition of specific performance indicators able to measure the potential impacts of the scenarios design in Chapter 3 regarding the baseline scenario. The experimental contribution is developed based on a real industrial case related to e-commerce logistics activities in Phnom Penh city (Cambodia). The numerical results show the clear benefit of using PI-hubs and especially on-demand and as-a-service transportation systems, which allows very substantial savings up to 55% for lead times, 61% for carbon footprints, and 75% for logistics costs. However, the study has some limitations, which are also discussed.

Overall, the study concludes that the use of certain PI concepts could drastically improve the performance of urban logistics activities in developing countries without any particularly large investment. The research proposes several future research perspectives, including the use of PI in different contexts and the development of a decision-making tools for PI implementation in urban logistics.

Keywords: Developing Countries, Physical Internet, City Logistics, Urban Logistics, Last-Mile Delivery, Simulation, Cambodia.